AD NUMBER

AD-657 482

CLASSIFICATION CHANGES

TO **UNCLASSIFIED**

FROM **RESTRICTED**

AUTHORITY

E.O. 10501; Nov 5, 1953

19990308180

AD NUMBER

AD-657 482

NEW LIMITATION CHANGE

TO

DISTRIBUTION STATEMENT: A

Approved for public release; Distribution is unlimited.

LIMITATION CODE: 1

FROM No Prior DoD Distr Scty Cntrl St'mt Assgn'd

AUTHORITY

ONR; Nov 5, 1960

~~RESTRICTED~~

UNCLASSIFIED

~~This document contains information affecting the national defense of the United States within the meaning of the Espionage Act, 50 U.S.C., 31 and 32. Its transmission or the revelation of its contents in any manner to an unauthorized person is prohibited by law.~~

AD657482

THE EFFECT OF HEAT UPON THE PERFORMANCE OF MEN IN HIGH SPEED AIRCRAFT: A CRITICAL REVIEW

Report No. 151-1-17
Project No. 20-M-1b
30 June 1948

19990308180

Report prepared by:

Division of Bio-Mechanics
The Psychological Corporation, New York

John D. Coakley, Acting Director

Lois Connell

Lois Connell, B. A.

Work authorized by:

Human Engineering Branch
Special Devices Center, ONR
Contract N6-ori-151
Task Order No. 1
Designation No. NR-783-004

Ltr dtd 6 Feb. 1947, Ser. No. 3831 SD from the Office of Naval Research, Navy Department, Sands Point, Port Washington, Long Island, New York

Jesse Orlansky

Jesse Orlansky, Ph. D.

John D. Coakley

J. D. Coakley, Ph. D.
Project Director

UNCLASSIFIED

TABLE OF CONTENTS

THE EFFECT OF HEAT UPON THE PERFORMANCE OF MEN IN HIGH SPEED AIRCRAFT: A CRITICAL REVIEW

I. Summary

1. The effect of high temperature upon human performance is examined by means of a review and evaluation of the relevant literature.

2. High temperature will be a problem for airplanes that fly at high speed. The sources of heat are friction of the aircraft skin with the air, cabin pressurization, waste heat from the power plant and other equipment, solar radiation, and possibly heat from the atmosphere itself. Already there have been reported such temperatures as 160°F. in the cockpit of jet aircraft, 275°F. on the skin of a V-2 rocket in flight, and 200°F. for the air at 400,000 feet altitude.

3. Some problems are encountered in describing the effects of high temperatures upon piloting high speed aircraft. Among these are: (a) the limited number of studies dealing directly with performance; (b) the concept of general performance deterioration, by virtue of which some test scores are treated as indices of all other behavior and the specific aspects of behavior (e.g. speed or accuracy) are neglected; (c) the concept of physiological adequacy, which is based on the assumption that behavior will remain normal as long as thermal equilibrium can be maintained; (d) the lack of detailed information as to just what specific activities are required in piloting a plane and which ones are of critical importance; (e) the difficulty of making comparisons between studies because of a failure to standardize experimental conditions. Standard procedures should be established for specifying the physiological, environmental, and psychological variables which are being studied.

4. A thermal zone in which men feel comfortable is described. There is no evidence that these thermal conditions interfere with performance at

sedentary tasks.

5. The following different thermal zones, as based on performance and the feeling of comfort, are delineated in the paper:

(a) a comfort zone, in which sedentary performance is normal;

(b) a marginal zone, in which discomfort is experienced but no appreciable impairment of performance has been demonstrated;

(c) a performance deterioration zone, in which the effects upon performance become more pronounced with prolonged exposure;

(d) a survival zone, in which slight effort can be expended; and

(e) a zone of failure due to heat collapse.

6. The combination of high temperature with other adverse conditions generally, though not always, produces an additive effect in disturbing human performance. High temperature lowers the tolerance to accelerative forces and to anoxia. It probably increases the incidence of motion sickness but it may reduce the frequency of aero-embolism slightly. However, the data for motion sickness and aero-embolism are not conclusive.

7. Data from industrial sources indicate that an increase of heat reduces production and increases the accident rate. While there is no reason to doubt that these effects are due to heat, such reports often lack the information required to evaluate them properly.

8. There are very few experimental studies of performance under hot conditions. Neither a wide variety of tasks nor a wide range of temperature-humidity-ventilation-radiation conditions has been sampled. Therefore, the conclusions stated below are tentative and subject to revision as experimental techniques are refined through further exploration. "Normal" performances on moderately complex tasks, requiring ability in problem solving, hand coordination, and visual attention, and requiring little physical effort, may be observed

at effective temperatures up to about 85°F. The deterioration in performance, which may occasionally be observed on these tasks in milder environments, is often statistically significant at temperatures just above 85°F. E.T. There is reason to expect that deterioration may occur at temperatures below 85°F. E.T. when, in addition, some physical effort is required, or when several tasks must be performed simultaneously, or when the tasks become more complex. However, data on these points are indirect and scanty. Heat probably reduces the willingness as well as the capacity to work. If this is true, individuals who have been working more closely to their limit may be expected to show greater deterioration.

9. Performance deteriorates significantly in less severe environments than those at which physiological equilibrium cannot be maintained.

10. As measured by the willingness of subjects to expose themselves to heat, temperatures as high as 120°F. are tolerable for about one hour, 107°F. for two hours, and 95°F. for four hours at the most severe humidities which occur under natural conditions. Even higher temperatures can be "endured" for short periods (e.g. 160°F. for one-half hour). Since these limits stand far above the performance tolerances, it may be presumed that a man's manual and intellectual activities would be very seriously restricted during such exposures.

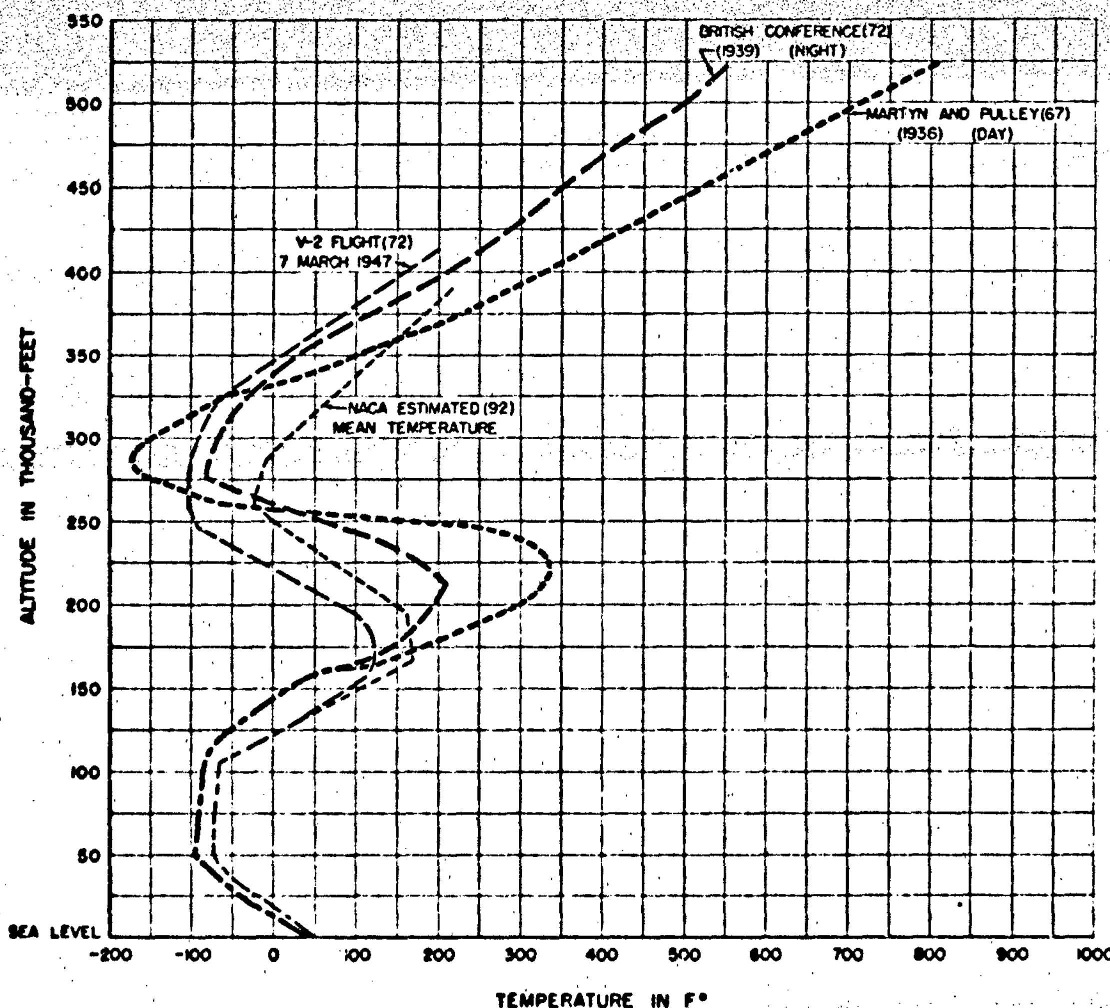

FIGURE I THE RELATION BETWEEN TEMPERATURE AND ALTITUDE, ACCORDING TO SEVERAL SOURCES.

II. Temperature Problems in High Speed Aircraft

Studies of the atmosphere have shown that temperature decreases 3.6°F. with every increase of 1,000 feet in altitude until it reaches -67°F. at about 36,000 feet, after which temperature remains relatively constant for a considerable distance. Temperatures as low as -94°F. have been recorded by sounding balloons which have explored the atmosphere up to 110,000 feet (51). Data from the recent rocket experiments show ambient temperatures as low as -100°F. at 260,000 feet. However, at still higher altitudes, the temperature appears to increase and is reported to be $+160^{\circ}$F. at 400,000 feet (72). Figure 1 shows the way in which temperature varies with altitude, as described by several investigators. Irrespective of some uncertainty as to the precise temperature to be found at any particular altitude, it is clear that the temperature gradient changes in magnitude and in sign several times and that both high and low extremes of temperature may be encountered.

Heat from the following sources may be encountered in high speed flight:

(a) friction between the skin of the airplane and the surrounding air
(b) heat arising from compression of the air for purposes of cabin pressurization
(c) waste heat from the power plant, electronic equipment, etc.
(d) solar radiation.

Heinemann (43) has reported the skin temperatures that may be expected on aircraft traveling at speeds between zero and 2,000 mph at altitudes from sea level to 35,000 feet. This is the heat rise due to compressibility of the air and does not take into account other sources of heat. Inspection of Figure 2 will show that the "human endurance" line (i.e. 100°F. and 50 percent relative humidity) intersects with the curves for "35,000 feet altitude and above" at about 950 mph true air speed. This intersection implies that for altitudes above 35,000 feet high temperatures become a problem at all speeds above about 950 mph. Furthermore, the problem becomes serious at much lower speeds when altitudes below 35,000 feet are considered.

AIRSPEED LIMITATIONS DUE TO TEMPERATURE LIMITS OF COMPONENT SYSTEMS

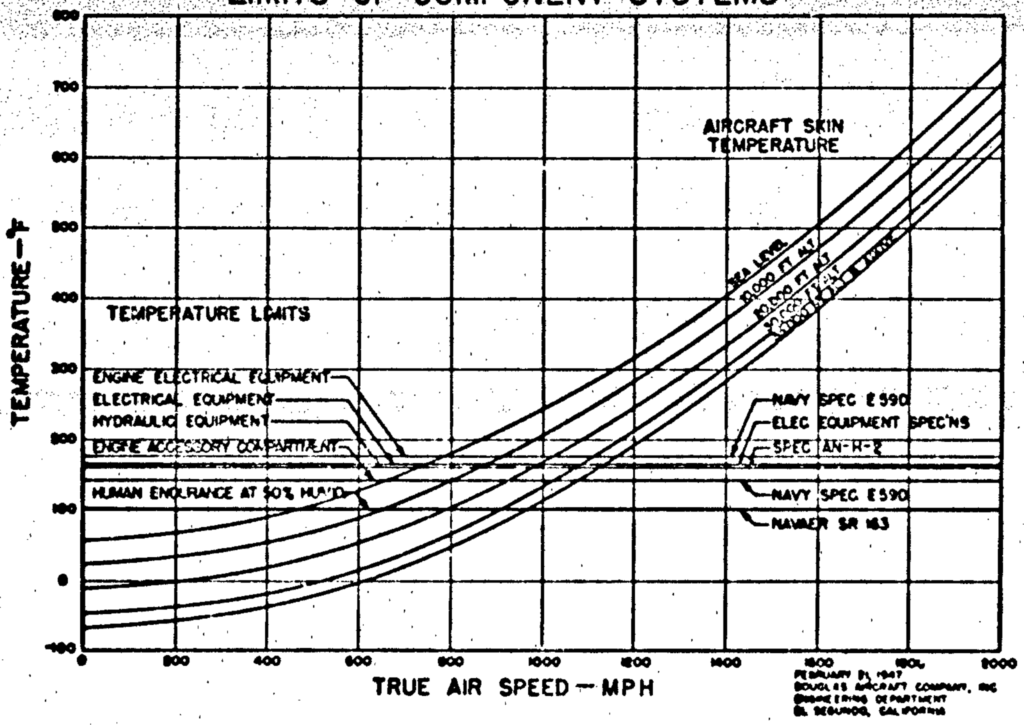

FIGURE 2 THE EFFECT OF AIRSPEED ON AIRCRAFT SKIN TEMPERATURE, COMPARED TO THE TEMPERATURE LIMITS OF COMPONENT SYSTEMS IN THE AIRCRAFT. TAKEN FROM HEINMANN (44)

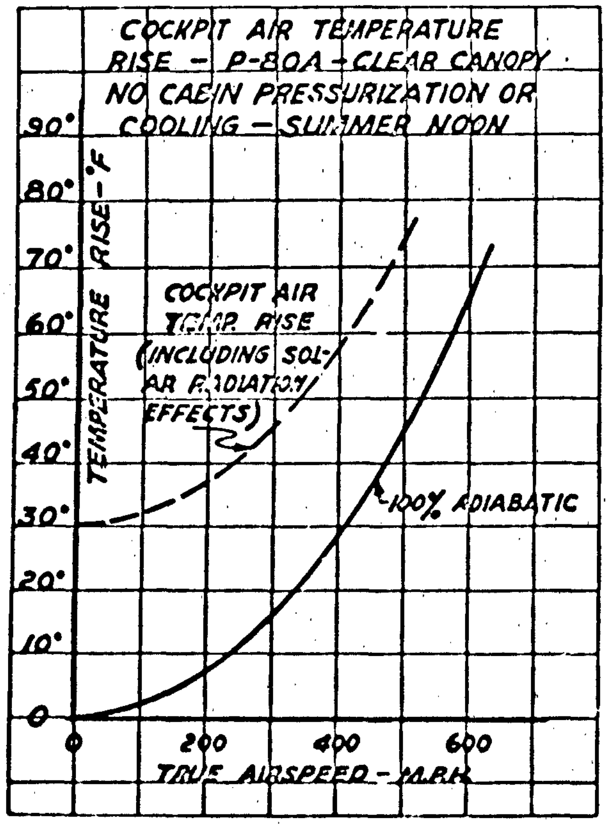

FIGURE 3 RISE OF COCKPIT AIR TEMPERATURE AT VARIOUS AIRSPEEDS IN A P-80A. TAKEN FROM JOHNSON (55).

[redacted]

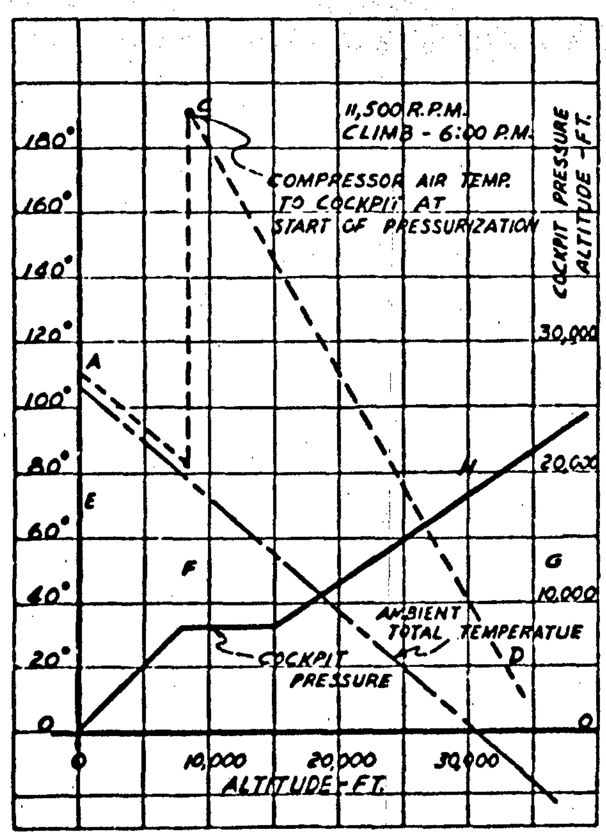

FIGURE 4 AIR TEMPERATURE WITHIN THE PRESSURE CABIN OF A P-80, EQUIPPED WITH A COOLING UNIT. TAKEN FROM JOHNSON (55).

The expectation that high temperatures will be encountered is borne out by flights at speeds presently attainable. For example, Johnson's graph, reproduced as Figure 3, shows the cockpit air temperature rise, including solar radiation effects, to be about 75°F. in a P-80A traveling at 500 mph. Figure 4, taken from the same paper, shows that the temperature of the compressed air entering the cockpit of a P-80 at the start of pressurization is 190°F. A cockpit temperature of 160°F. recorded during a high speed run in a P-84 was reported at the meeting of the Committee on Aviation Medicine of the National Research Council on 22 June 1948.

According to Stalder and Jukoff (85), the effect of solar radiation upon skin temperature is small at altitudes of less than 75 miles. Solar radiation, however, becomes the major influence upon skin temperature at altitudes above 150 miles, where skin friction and cooling are negligible factors. The magnitude of heat rise due to solar radiation upon a person in a plane has been estimated to range from 4°F. at 5,000 feet to 31°F. at 110,000 feet (56). The relationship between solar heat load and total heat load, particularly with respect to its significance for the design of clothing, has also been examined by Blum (12).

Under special circumstances, high temperatures may be observed even in conventional aircraft. Thus, Fawcett (28) reports that, in flights over desert terrain, the temperature has reached 140°F., accompanied by humidities up to 90 percent and air movement velocities up to 50 miles per hour. Temperatures as high as 178°F. have been recorded on stationary aircraft parked in the open (28).

Further data on the skin temperatures to be expected at high speeds are available from measurements made on V-2 rockets. These temperatures were measured with platinum resistance wires designed to record temperatures up to

[redacted]

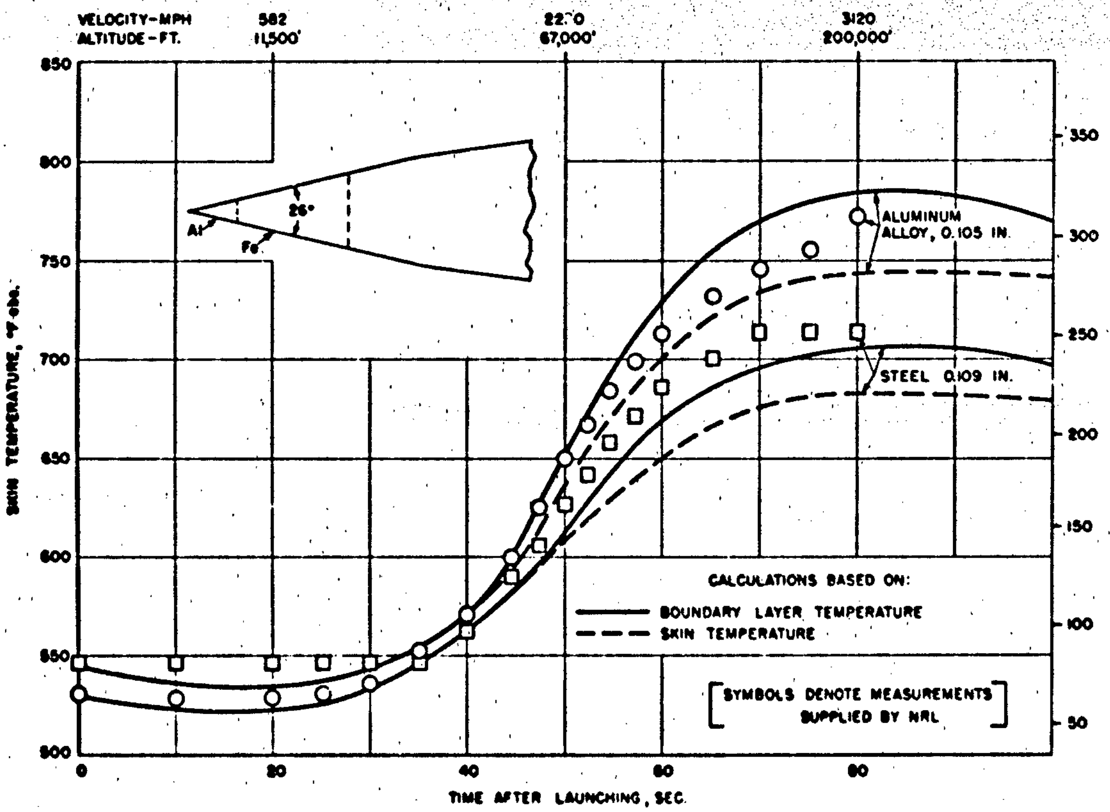

FIGURE 5 TIME HISTORY OF CALCULATED AND MEASURED SKIN TEMPERATURES DURING ASCENDING PORTION OF A V-2 ROCKET FLIGHT PATH. TAKEN FROM A NACA STUDY (52).

1300°F. and were telemetered to a receiving station on the ground. Satisfactory data collected for the middle portion of one flight show skin temperatures varying between 167° and 374°F., the higher temperatures being observed in the forward part of the rocket (41). More complete data from another flight are shown in Figure 5. Evidently skin temperature may approach 275°F. 80 seconds after launching. This temperature occurred at an altitude of 200,000 feet and a speed of 3,000 mph (52). Figure 1, moreover, shows that ambient temperatures at this altitude have been estimated as 80° to 300°F.

Thus, for several reasons, it is evident that high speed flight may involve the exposure of men to temperatures which require the use of protective measures. Heretofore, the concern with temperature in aviation has largely been to protect the pilot against cold. Thus, Armstrong's (4) book on aviation medicine devotes more than three pages to the topic of cold and only 20 lines to heat; Gemmill devotes seven pages to high temperature, but does not discuss heat as related to aircraft in flight (37). The advent of high speed flight and pressurized cabins emphasizes the previously unimportant problem of heat. McFarland (68) was among the first to devote extended attention to heat as a problem associated with high speed aircraft. At present, cold is still a problem encountered in the operation of several types of aircraft. However, the effects of low temperature upon performance are not discussed in this paper, which is devoted entirely to the effects of heat.

III. Methodological Problems Involved in Determining the Effect of High Temperature upon Pilot Performance

Many of the practical problems posed by aircraft designers and engineers take the form of a question as to the maximum (or minimum) temperature at which a pilot or another aircrew member can be expected to carry on his duties without undue deterioration of performance. Ideally, one would have a set of temperature tolerances for performance, perhaps in the form of one or more charts, to answer such questions. Unfortunately, there are at present several reasons why such precise specifications cannot be devised. An understanding of the limitations of our information is prerequisite to use of the facts which the literature contains. Six methodological problems are discussed below.

1. One of the important reasons why precise temperature tolerances for human performance are not generally available is that studies in which specific performances have been measured are in the minority. A large portion of the literature is given over to studies dealing with the mechanism of heat regulation and related physiological and medical problems.

2. Studies of the interrelations of performance and temperature may have been delayed because of the concept of general deterioration of performance. According to this concept, the specific behavior chosen for observation is thought of as an index of behavior at large; and, in terms of this restricted sample of behavior, the performance is judged normal, or temporarily below normal. The danger inherent in such a doctrine is that it is too gross. The investigator attempts to deal with behavior *en masse* rather than to inquire specifically whether speed, accuracy, dexterity, strength, decision time, coordination, or steadiness are adversely affected by given temperature conditions. It would be unwise to assume, without evidence, that all of these characteristics of behavior are similarly affected by a particular thermal

willingness to — capacity

stress placed on the organism.

activities

It is a well-known fact that some activities can continue under conditions which would make it impossible to engage in other activities. When the organism is exposed to moderate stress, impairment may be evident in some but not in all of the psychological performances. Under anoxia, for example, vision is impaired at an altitude of 10,000 feet while psychomotor performance is not noticeably affected. Certain types of stress may produce local and specific impairment. Thus, cold may slow up performances involving motion of the extremities but not appreciably impair the ability to see. Since environmental stress may also produce discomfort, the impairment may be related to distraction and interference with performance. That is, the willingness to work, rather than the capacity to work, may be reduced. The notion of a single behavioral index to indicate general performance deterioration seems to be theoretically unsound.

e.g.

3. Another closely related point of view which has influenced the development of performance studies involves the concept of the physiological adequacy of man. According to this view, measurements of body temperature, perspiration, and the like are employed as indices of man's physiological condition. Tolerances are set in terms of temperature conditions at which thermal equilibrium in the body begins to disappear. This view presumes that performance will not be impaired so long as the regulatory mechanisms are effective and homeostasis prevails. As compared with the psychologist's approach to temperature through performance, the view of physiological adequacy has much to recommend it; it is simpler in concept, probably simpler so far as the required research is concerned, and should yield a workable set of tolerance values. The limitation of this view, however, is that some of the more delicate and complex behavioral activities, critical in their importance, may be significantly altered

by a thermal environment not sufficiently extreme to cause large changes in the physiological criteria. This is a problem of the sensitivity and adequacy of the physiological criteria; or, in the phrase of the statistician, this is a matter of both the reliability and the validity of the indices. The problem of the correlation between measured bodily condition and performance adequacy appears to invite research.

4. The determination of temperature tolerances for pilots requires either a direct study of piloting a plane under experimentally controlled thermal conditions or a study of the constituent activities which are involved in piloting a plane. The direct method has not been employed although it offers several advantages as well as important difficulties with respect to equipment, safety, experimental control, and cost. The indirect method implies that the constituent activities must be known prior to experimentation. A job analysis of sufficient detail to describe just what the pilot does is not yet available. In the absence of specific information, one may probably assume that an adequate performance on the task of piloting an airplane requires much skill in motor coordination and that intelligence, freedom from tension, and the ability to perform in the presence of stress are also required. Should this be true, any influence of temperature upon motor coordination, personality, or intelligence would also affect pilot performance. The absence of an authoritative job analysis not only makes it difficult to judge which of the studies of heat are relevant to the pilot's task, but also interferes with a full examination of the effects of other types of stress.

5. From the standpoint of technique, a consideration of the effects of temperature requires that humidity and ventilation be specified, for these variables modify the effects of temperature. Attempts to integrate these three variables into a single measure have resulted in the development of several

environmental indices, among which are effective temperature (97,99), equivalent warmth (8), and standard operative temperature (which includes radiant temperature as well) (32). These indices are defined in Appendix A, together with illustrative charts. Unfortunately, investigators in this field are not agreed that a single index or a single measuring instrument applies equally well to all situations.

The experiments on the effects of high temperature have been carried out under a variety of conditions, and this variety sometimes complicates direct comparison of the findings. Many combinations of dry and wet bulb temperature and rate of air movement are possible, and investigators have not always confined themselves to a standard practice in their experiments. There is a lack of uniformity also in the physiological measures which have been observed and in the manner in which these data have been collected. The type of heat load imposed upon the subjects is not always obvious because few attempts are made to partition the conductive, convective, and radiational loads.

6. A temperature tolerance for performance, called for short a performance tolerance in this paper, is defined as the temperature above which some designated performance cannot be carried out. There may well be as many performance tolerances as there are types of tasks. Some studies which are concerned primarily with physiological problems may provide information useful in delineating these performance tolerances. For example, a performance tolerance must fall at a less extreme set of conditions of temperature, humidity, and ventilation than that at which some dramatic syndrome, such as heat stroke, regularly occurs. Obviously, a highly integrated performance, such as that required of a pilot, cannot be expected at temperatures more extreme than those at which delirium, coma, or collapse generally occur. The onset of such disturbances implies that the human capacity for directed, purposeful, and organized

behavior has been exceeded. Thus, physiological limits can be used to define the upper possible temperature limits for unimpaired performance. However, when such a criterion is used, there must remain considerable uncertainty as to the true performance limit. Without more information, it is impossible to say how the efficiency of performance is affected under the milder conditions which precede the onset of serious symptoms.

In the following section, material will be presented which shows some of the effects of heat in conjunction with other types of physiological stress. Thereafter the influence of high temperature upon several varieties of performance will be described, as gathered from studies of this problem in industrial as well as in laboratory settings. This report does not provide a complete survey of the physiological literature in the field.* It is restricted to those studies which appear to have a direct bearing on the problem of human performance.

---

*For general references on the physiology of temperature the reader is referred to Best and Taylor (10), Bartley (5), McFarland (68), and the volume on "Temperature" (103). There are also the Handbook published by the American Society of Heating and Ventilating Engineers (101) and the well-known works of Adolph (1), Dill (23), and Bazett (6). Hemingway (44), Brobeck (15), and Gagge and Herrington (34) have provided excellent reviews of the most recent studies of the physiological reactions to heat.

IV. Effects of Heat upon the Tolerance for Other Types of Physiological Stress

A summary of the effects of heat upon man reveals findings which can be qualitatively distinguished as follows: (1) A succession of effects upon the human subject may be observed as ambient temperature gradually rises above some normal, comfortable value. First, the subject may report mild discomfort; and then, with further increases in temperature, his ability to do simple, sedentary tasks becomes limited; his temperature regulating mechanisms are called into full activity and then embarrassed as thermal equilibrium disappears; then collapse or death may occur. Each of these effects can serve as the basis for one particular kind of tolerance. Thus a series of tolerances can be defined and appropriate experimentation undertaken to determine the value of each. Determination of such tolerances involves the same general theoretical and technical problems as the measurement of any other kind of threshold in the fields of physiology or psychology. Such tolerances can be measured when thermal conditions represent the only kind of stress placed upon the subject or when some additional stress, e.g. lowered atmospheric pressure, is applied. In both cases a heat tolerance is being determined. (2) A qualitatively different effect would be observed in an experiment devised to measure tolerance to some other stress. For example, it might be observed in a centrifuge experiment that a rise in ambient temperature would lower the acceleration tolerance. Thus any specification of permissible temperatures must take account not only of temperature tolerances *per se* but also of the effects that temperature may have upon other tolerances. Several examples of temperature effects upon other tolerances will be described to serve as an advance warning that temperature tolerances alone, no matter how precise they may be, do not necessarily give a complete answer to the temperature problems encountered in the operation of high speed aircraft.

The simultaneous imposition of several environmental stresses upon an individual may be expected to have an additive and, possibly, a cumulative effect in disturbing his performance. This supposition is supported, not without some exception, however, in several studies reported below showing the effect of heat in conjunction with some other stress, such as acceleration, noise, or anoxia. In the cases where an additive effect due to stress is not demonstrated, this may be because the magnitude at which one of the variables, as for example noise, becomes a stress was not reached in the experiment.

1. Tolerance to accelerative forces is lowered by high temperatures. Code et al.(19) have reported that the overall *g* tolerance of centrifuged subjects was 0.8 *g* lower at temperatures which averaged 89°F. as compared with 63°F. This change is attributed to the reduced effectiveness of vasomotor compensations in the presence of the higher temperature.

2. Motion sickness, according to Hemingway (45), may be more prevalent in the presence of hot than of warm or cold temperature. Using a swing to produce motion sickness experimentally, he tested approximately 1,000 men in the AAF at temperatures from 32°F. to 104°F. Forty-five percent of all the men showed some symptoms of motion sickness. Although there was no significant difference in incidence of sickness in the cold or warm environments, the incidence was greater at temperatures of 96°F. to 104°F. The group of 11 individuals tested at the latter temperatures is too small, however, for the results to be significant. The author concluded that the apparent beneficial effect of cool air on motion sickness is probably subjective.

3. Viteles and Smith (91) exposed six men to effective temperatures up to 87°F. (98°F. dry bulb and 81.5°F. wet bulb) over a period of seven weeks. Noise levels of 72, 80, and 90 decibels (db) were employed during experimental sessions in which a series of seven tests was administered: Mental Multiplica-

tion, Number Checking, Lathe Test (hand coordination), Typewriter Code (scrambled letters), Locations (spatial relations test), Pursuit (visual maze tracing), and Discrimeter (complex reaction time). There was a deterioration of performance as measured by fall in work output and increase in error rate on all tests at 87°F., effective temperature, as compared with 73°F., effective temperature. This result will be examined more carefully in Section V. The present interest centers in the fact that the poorest performance occurred at 72 db for three of the seven tests, at 80 db for one test, and at 90 db for the remaining three tests. (Thus, there is no consistent tendency for greater deterioration to be associated with any one of the three noise levels tested.) Furthermore, a questionnaire indicated that the subjects, without disturbance of attitude, adjust rapidly to sound levels as high as 90 db. The sound levels and temperatures employed in this experiment were selected because they approximate some conditions that may be encountered at work stations aboard ships. Higher levels, both of sound and temperature, may be expected on certain aircraft, but experiments have not been found in which the observations have been extended to such conditions.

4. The combined effects of temperature and anoxia were shown by comparison of the incidence of failure due to anoxia for two experimental groups with a control group of 2,998 young men who made routine indoctrination runs in a low pressure chamber. Men in the control group wore winter flight clothes at "18,000 feet" in a chamber refrigerated to 0°F. (50). The first experimental group consisted of 611 men wearing dungarees or summer working uniforms during runs at 18,000 feet with chamber temperatures ranging from 75°F. to 97°F. The second experimental group consisted of 359 men wearing heavy winter flight gear over summer uniforms or dungarees during runs at 18,000 feet and temperatures ranging from 65° to 97°F. Men in this latter

group were permitted to remove their gloves and leave their jackets half-opened during the heated period.

The subjects were exposed to anoxia during the ascent and for ten minutes at 18,000 feet. Thereafter, they put on oxygen masks. Subjective rating scales were filled out prior to the run and just after the men began to breathe supplementary oxygen. The results of the experiment are shown in Table I, which indicates the essential conditions for each group. Each of the experimental groups is subdivided on the basis of the prevailing temperature. The table shows the number of subjects in each group and subgroup, and thereafter the number of collapses and impending failures. The percent of failures

TABLE I

Incidence of Anoxic Failures in Heated and Chilled Runs
in a Low Pressure Chamber
Data from Houston et al.(50).

Type of run	Chamber temperatures (average at 18,000 ft.)	No. subj.	Collapse*	Impending failure**	Total No.	Failures (percent)
Control	0°F.	2998	2	9	11	0.36
Wearing light clothes	65° - 75°F.	0	0	0	0	0
	76° - 85°F.	542	4	5	9	1.7
	86° - 97°F.	69	1	0	1	1.5
	Total	611	5	5	10	1.6
Wearing winter flight gear	65° - 75°F.	99	1	1	2	2.0
	76° - 85°F.	194	4	1	5	2.6
	86° - 97°F.	66	0	3	3	4.5
	Total	359	5	5	10	2.8

*Includes Vasomotor and Cerebral types.
**Includes Impending Vasomotor Collapse.

[redacted]

high anoxia + temp.

is shown in the last column of the table. With a single inversion, each of the experimental groups reveals a trend of more failures at higher temperatures. The incidence of failure in each experimental group is considerably greater than in the control. In particular, there were nearly 12 times as many failures in the group wearing heavy flight gear at high temperatures as in the control group (4.5 percent as compared with 0.36 percent). Subjective complaints at the higher temperatures were also more frequent. A further, more careful study by the same investigators has been examined and found to confirm these findings; but the material has not been published.* A report which shows a higher rate of anoxic failure in certain older and warmer Navy low pressure chambers (lacking temperature control) may be considered also to verify these findings (102). Vasomotor collapse is a common syndrome of anoxia and of exposure to heat, and it is reasonable to suppose that there may be an additive effect of simultaneous exposure to heat and anoxia as the data, in fact, appear to indicate.

5. The effect of high temperature upon aero-embolism is difficult to assess, although it appears that low temperature increases the incidence of aero-embolism in low pressure chambers. Anthony (2) found that at 38,000 feet there are 12 percent fewer cases of bends at 100°F. than at 55°F. Griffin (40) reports a lesser incidence of bends at 35,000 feet among subjects protected against the cold than among those who were not protected. Motley (71) found a slight reduction in frequency of bends among 7,664 young men as temperature increased from 75°F. to 95°F. at 38,000 feet, but the observed variation is not significant. Smedal (84) found a slightly higher incidence of bends among exercising subjects (1,731 men at 26,000 - 30,000 ft chamber altitude) at room temperature (70° to 80°F.) than at low temperature (-40° to -50°F.). However, the incidence of bends among resting subjects at both temperatures was so low

*Private communication from C. P. Seitz.

that no consistent trend could be attributed to temperature. In view of these findings, no conclusion appears warranted at this time concerning the effect of high temperature on aero-embolism. This example is included merely to suggest that elevated temperatures do not always lower other tolerances significantly.

V. The Effect of Heat upon Several Kinds of Performance

Attention is now invited to the effect of high temperature upon specific performances. Information of this kind falls into two categories, according to source, i.e. industrial and experimental. Some industrial reports indicate a relation between high temperature (and occasionally humidity) and production data and accident rates. Such data must be evaluated cautiously because certain unreported factors, such as accident prevention measures, safety education, medical supervision, and industrial morale may also affect the efficiency of production. Often, in these studies, consideration is not given to whether the reported effects of temperature are statistically significant. With these reservations in mind, some information from industrial sources may be presented to indicate that high temperature probably reduces production.

A. Industrial Data

1. Coal-mining. According to Bedford (9), miners working at a coal-face where the effective temperature was 81°F. produced 41 percent less than men working where the effective temperature was 66°F. As measured by records of employee sickness, Vernon et al.(90) found that there was a 3 percent loss of production time when the temperature was below 70°F.; there was a 4.5 percent loss when the temperature ranged from 70° to 79°F. and a 4.9 percent loss when the temperature was 80°F. or more. Vernon et al.(89) report that 138 miners observed for an average of 96 minutes rest 7 minutes per hour while working in favorable environments and 22.4 minutes per hour in unfavorable environments. In the latter condition, 9.6 minutes is required to fill a one-half ton tub of coal as compared with 8 minutes at the lower temperature.

2. Tinplating. In a group of tinplate factories, the rate of production in the hottest month of the year was 10 percent less than in the coldest month. It was estimated that this figure would reach 30 percent in the worst-

ventilated factory where seasonal temperature variations were most apparent. According to Bedford (9), there are variations in output in the steel, glass-bottle making, and allied industries that clearly show the influence of temperature upon performance.

3. Linen and Cotton Weaving. High temperatures and high humidities are favorable for the weaving process, but their adverse physiological effects on the weavers reduce output when the temperature goes above 75°F. (9).

4. Gold Mining. Studies in the gold fields show that these miners have considerable tolerance to heat. Caplan (27) reported that heat casualties were rare in the Kolar Gold Fields. He found acclimatized men could "work" in dry bulb temperatures of 110° to 120°F. However, heat casualties began to appear at wet bulb temperatures of 91°F. to 93°F. and were frequent at 94°F. and 96°F. According to Eichna (27), Dreosti and Weiner found that nude, well-acclimatized men could retain thermal equilibrium for at least one hour while working at a rate of 9,000 ft lbs per hour in a completely saturated environment of 95°F. in the deep gold mines of South Africa.

5. Munitions Factory. A study made at a large munitions factory during 1914 to 1918 showed that accident rate is related to temperature. Average temperature and the number of cuts and other minor accidents during each working period were recorded, and the base accident rate was determined for those periods when the temperature was between 65°F. and 69°F. There was a 40 percent increase in the accident rate among the men when the temperature rose above 75°F. (9).

One can scarcely doubt that production is reduced during prolonged exposure to high temperatures. Acclimatization undoubtedly improves the subject's ability to perform under exposure to heat as the report from the Kolar Gold Fields illustrates. Wet bulb temperatures up to 91°F. apparently can be

tolerated during heavy work. The studies of Bedford and of Vernon show that some deterioration in heavy work may be noted at or below 81°F. and 79°F. The studies of weavers and munitions workers place the upper temperature limit for normal performance (heavy work) at 75°F.

The applicability of these studies to aircrew men is questionable. On the one hand, it may be argued that aircrew men are engaged in lighter work, and accordingly should be able to tolerate temperatures above 75°F. without adverse effects. On the other hand, the accuracy, delicacy, and complexity of the pilot's performance may evoke temperature limitations which do not apply to heavy work. Conceivably, heavy work could persist under conditions in which accuracy or fine coordinations were severely limited. A group of experimental studies will now be examined to throw further light on these problems.

B. <u>Experimental Studies</u>

The very considerable advantage afforded by studies performed in a laboratory or under precisely recorded conditions in the field is that the important facts are likely to be available for analysis and evaluation. Some of the following studies deal with a particular type of performance which may not appear to be related to pilot performance. In fact, no study has been found in which pilot performance under conditions of heat is examined. Accordingly, attention is directed to such studies of performance as may prove useful in making some deductions concerning the effect of heat upon pilot efficiency. The underlying reasoning is that if some aspect of performance is adversely affected by a particular temperature and this aspect of performance is presumably required in the operation of a plane, pilot performance will show some deterioration at the given temperature.

1. <u>Reaction Time.</u> A previous paper in this series examined the effect of temperature upon reaction time (29). The general conclusion was that

"reaction time does not vary significantly with high ambient temperatures up to 117°F. provided the wet bulb temperature does not exceed about 86°F.". This conclusion is applicable to reaction time as defined in traditional laboratory studies, i.e., the subject is prepared and forewarned of the stimulus, the stimulus is relatively simple, and the response is all-or-none. The time for reacting may lengthen at temperatures lower than 117°F. dry and 86°F. wet bulb when the conditions of the classic experiment are altered. Performance on a task requiring a complex response is known to lengthen under conditions of stress at which simple tasks appear to be unaffected.

2. Visual Attention. The next four studies to be described comprise a series in which Mackworth examined the influence of heat upon four different performances. The tasks were called visual attention, Morse code reception, pursuitmeter, and weight pulling. Table II indicates by a mark (x) the temperature conditions in which the several experiments were carried out:

TABLE II

Temperature Conditions for Four Performance Studies
Reported by Mackworth (60,64)

Experiment	Room temperature °F.								
	Dry bulb	65	75	85	90	95	100	105
	Wet bulb	60	65	75	80	85	90	95
	Effective	61	69	79	83	87.5	92	97
Visual attention			x	x		x		x
Morse code reception				x	x	x	x	x
Pursuitmeter				x	x	x	x	x
Weight pulling		x	x	x	x	x	x	

All the experiments involved three hour work periods in the heat except in the

visual attention task where a two hour period was employed. The air velocity in the room was always 100 feet per minute. The subjects were dressed only in gym shoes and white tropical shorts. Plenty of unsalted water was at hand, and each man had an additional daily ration of 10 grams of salt.

The effect of heat is to increase the percentage of missed signals in a visual attention task (61,64). A "clock test" was used to produce a situation of prolonged visual attention similar to that encountered by radar operators and others in watch-keeping duties. A black pointer jumped once every second, like the second hand of a large clock, 100 of these movements making the full circle. At irregular intervals, the pointer moved through double the usual distance, and the subject was required to press a Morse key whenever this occurred. An error consisted of each instance in which the subject failed to respond within 8 seconds to the larger movement, 48 of which were presented in the two hour test periods.

The 69 subjects practiced the test and were acclimatized to heat over a period of two weeks by daily exposures of two hours to effective temperatures of 87°F. on the first day, 92°F. on the second day, and 97°F. on the third day and thereafter.

The data for percent of missed signals and for average response time are presented in Figure 6. Statistical analysis of the data for errors shows that the minimum which falls at 79°F. E.T.* is reliably different from the other three values. At present no significance is attached to the improvement for 79°F. E.T. as compared with 70°F. E.T. except that it indicates normal performance up to at least 79°F. E.T. As compared with 79°F. E.T., 87.5°F. E.T. introduces demonstrable deterioration in vigilance and yet does not cause slowing of the particular response required of the subject. There can be no question

*Effective temperature.

that visual attention is required of pilots and apparently this activity is affected adversely at 87.5°F. E.T. If certain aspects of flight conditions can be presumed to depend upon the type of vigilance measured in Mackworth's experiment (other things being equal), some deterioration in performance may be anticipated at 87.5°F. E.T. and above.

3. Morse Code Reception. In another study, Mackworth (62) examined the effect of heat on the performance of 11 men with different degrees of proficiency in listening to and writing down Morse code messages, a task which involves high speed, semi-automatic work. The men were acclimatized to heat by exposures for three hours to an effective temperature of 97°F. 5 days each week over a period of 11 weeks for one sub-group and 6 days a week over 7 weeks for another sub-group. During this period, the sub-groups were given 5 and 7 weeks of practice, respectively, in receiving Morse code messages, the difference in practice being designed to bring them to a common level of proficiency. The test periods in the five experimental environments were also three hours long, during which time the men received and wrote down code messages at the rate of 22 five-letter-and-number groups per minute. Three-minute rest periods were allowed after every 16 minutes of work. The men were informed of the accuracy of their work.

The subjects were arranged in rank order of ability and placed in three groups on the basis of their performance in the two mildest environments. In increasing order of ability, these groups were called "competent," "very good," and "exceptional" operators. Figure 7 presents the average number of mistakes per man per hour for the three groups. It may be noted that the temperatures chosen for study differ from those of the preceding study. Several relationships are evident in Figure 7. (1) The general trend of all the curves suggests positive acceleration. Such a trend implies that performance

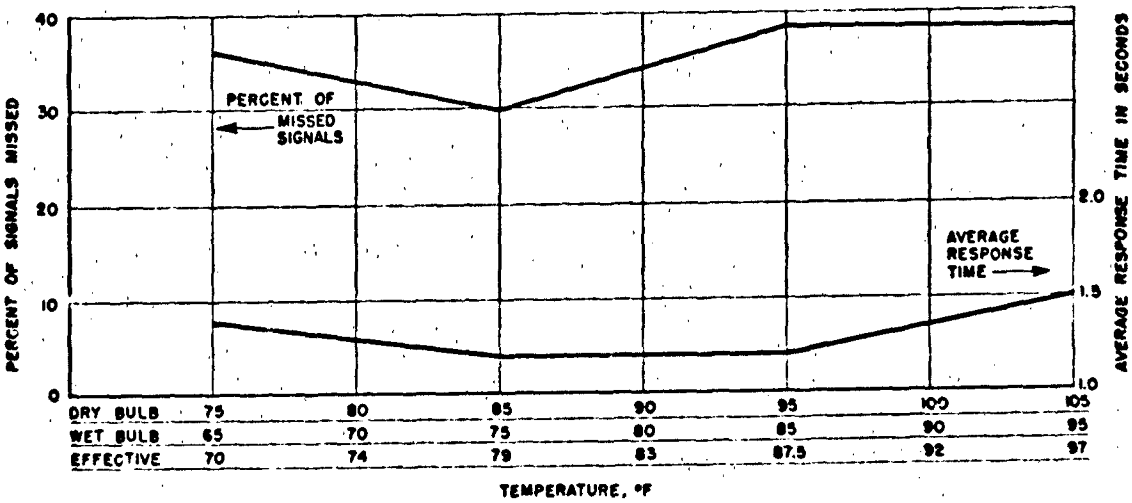

FIGURE 6 PERCENTAGE OF MISSED SIGNALS AND AVERAGE RESPONSE TIME ON A VISUAL ATTENTION TASK (CAMBRIDGE CLOCK TEST) AT VARIOUS ROOM TEMPERATURES. DATA FROM MACKWORTH (64).

[redacted]

Motor Code

begins to deteriorate gradually at first and then more and more rapidly as the environment imposes greater thermal stress upon the operator. Since performance deteriorates gradually, some criterion must be established in order to judge the level of heat at which the performance becomes unacceptable. More deterioration may be permissible in some situations than in others. (2) While for all three groups the striking deterioration occurs at the highest temperature studied, there is a suggestion that the onset of deterioration occurs at lower temperatures for the less accomplished individuals. (3) The performance impairment is greater for the less proficient telegraphers. Both the number of errors and the percentage increase in errors are much greater for the "competent" and "very good" operators than for the "exceptional" men.

Two practical implications appear to follow from this study: (1) Training to a higher level of skill may serve as a partial antidote to the adverse effects of temperature stress upon behavior. (2) The temperature should be kept below 92°F. E.T., in order to avoid deterioration of performance on this type of task.

Implications

4. Pursuitmeter Performance. In a third study, Mackworth (60) asked 10 subjects to practice for a week on two pursuitmeters which differed in that manipulation of the control lever by the subject required light work on one apparatus and heavy work on the other. A mechanically controlled pointer moved to-and-fro in an erratic manner. The subjects raised or lowered a horizontal lever to follow with a second pointer the rapid changes in position of the machine pointer. Any separation of the pointers was mechanically cumulated to provide a total error score at the end of each run. The subject's lever on the heavy pursuitmeter carried a 50 lb weight attached close to the grip. Bimanual operation was necessary. On the light pursuitmeter a finger control, rather than a weighted lever, was installed. While working for three hours

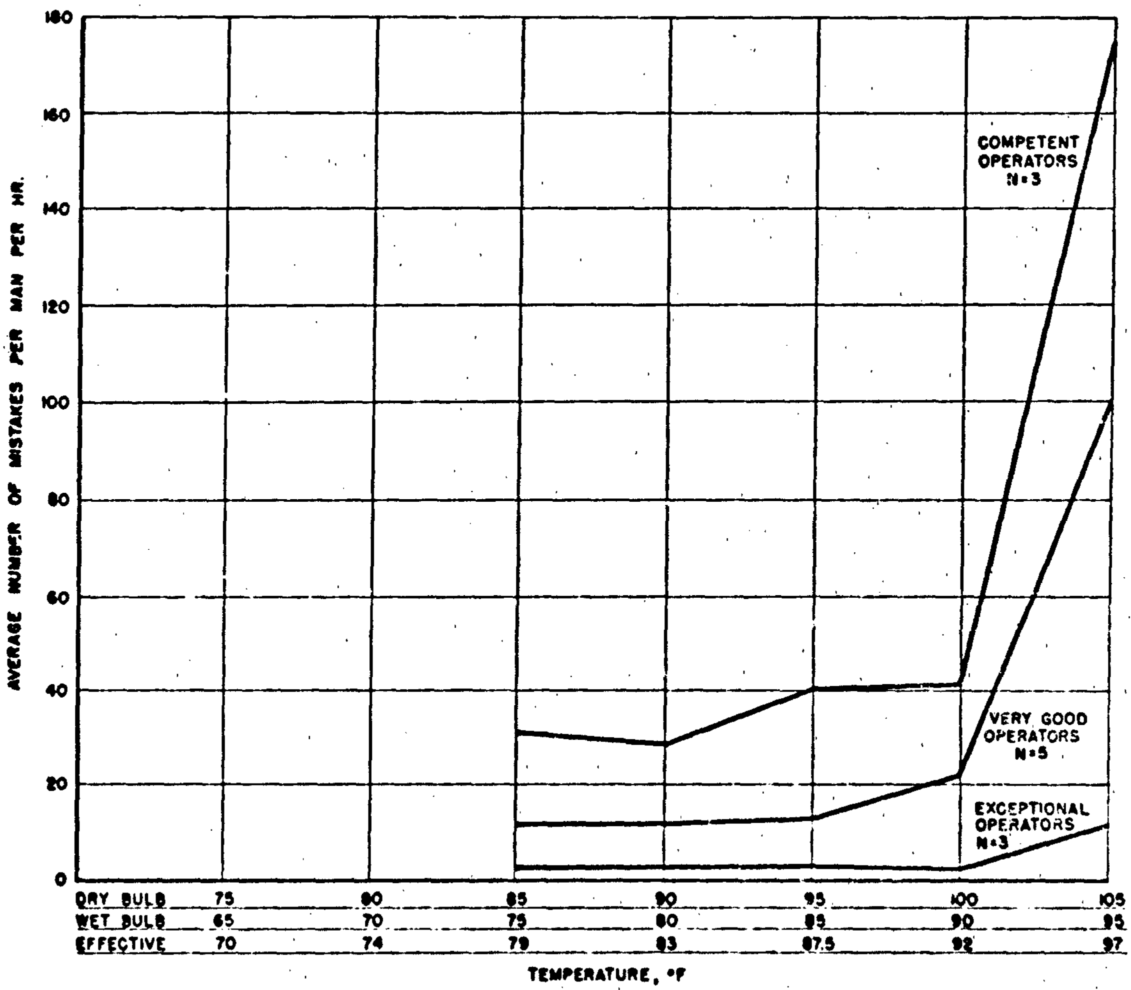

FIGURE 7 AVERAGE NUMBER OF MISTAKES MADE BY 11 RADIO OPERATORS RECORDING MORSE CODE FOR 3 HOURS AT VARIOUS ROOM TEMPERATURES. DATA FROM MACKWORTH (62).

at these tasks, the subject was exposed to one of several temperature conditions.

Results

Figure 8 shows the average error score on the two tasks during each of the three hours of work in the different environments. Several items of interest may be pointed out. (1) More errors occur on the test which requires greater manual exertion. (2) On both tasks, the number of errors per hour increases progressively with increased duration of work and exposure to heat. (3) The rate at which performance deteriorates during the exposure to heat is greater at the higher temperatures. (4) Impairment is not evident at 87.5°F. E.T., but is measurable at 92°F. E.T. for those tasks. The practical implication from this study is that the temperature should be kept below 87.5°F. E.T. in order to avoid deterioration in performance on a task involving motor co-ordination for long periods of time.

5. Weight Pulling. Using an arm ergograph, Mackworth (63) had 30 subjects bend and straighten their arms while grasping a handle attached by a rope running over a pulley to a 15 lb weight. The subjects were instructed to raise and lower the weight once every two seconds until they were incapable of further work. The work load was about 30 ft-lbs every 2 seconds, since the weight moved a maximum of 2 feet. Measurements of the respiratory exchange, made by a breathing bag method, suggest that the task may be considered a heavy work load since muscular energy was used at the rate of about 310 k cal/hr. Work output was measured in arbitrary absolute units, where a two-inch trace on a tape recorded a movement of the weight through a distance of two feet. The men practiced the task and were acclimatized to heat over a period of two weeks by daily exposures of three hours to effective temperatures of 92° to 95°F.

The tests were accomplished under two conditions of incentive.

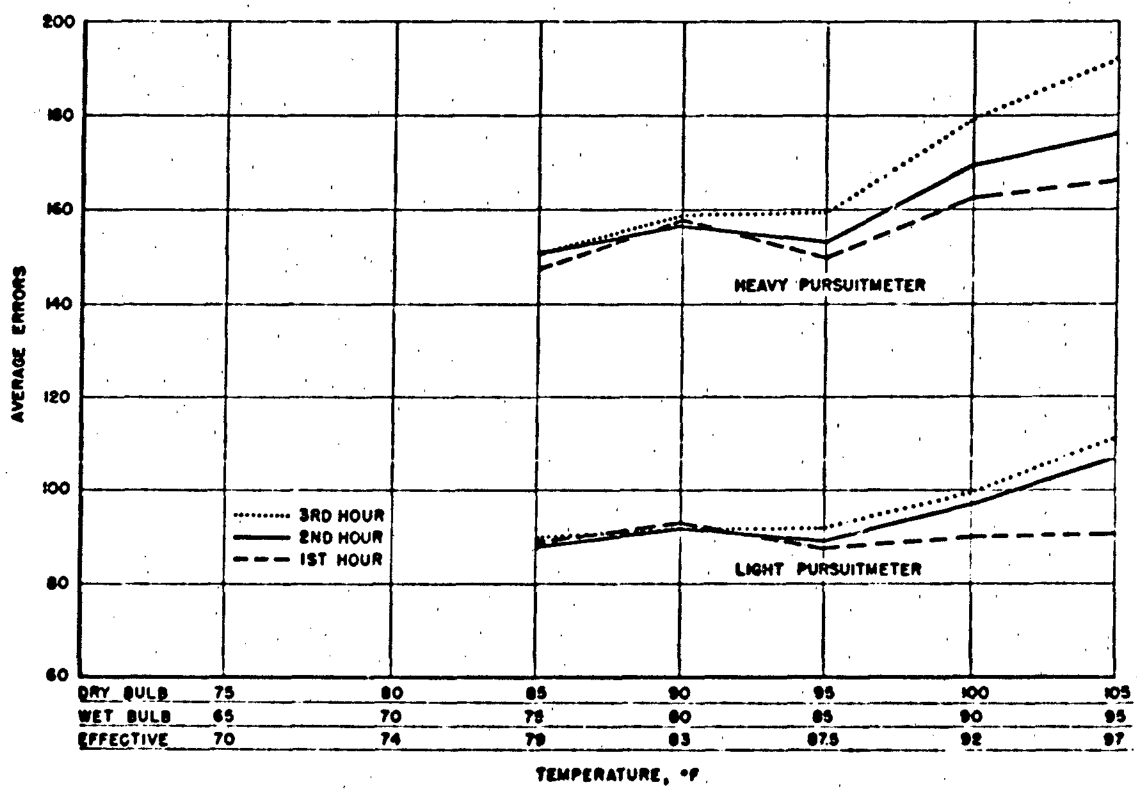

FIGURE 8 AVERAGE ERRORS BY 10 MEN ON LIGHT AND HEAVY PURSUITMETERS DURING 3 HOURS AT VARIOUS ROOM TEMPERATURES. DATA FROM MACKWORTH (60).

Under the low incentive or control condition, the men worked alone and with no knowledge of their results. Under the high incentive condition, the men observed the tracings of their work effort and were encouraged by the experimenter to exceed their previous scores and those of the other men. The men acted as their own controls since each of the 30 subjects worked under both conditions of incentive. As shown in Figure 9, there can be no doubt concerning the decrement of work output with increased environmental stress under both conditions of incentive. At the most extreme temperature, this is a reduction in output of 36.1 percent from their best performance when they are strongly motivated and 39.8 percent when they are less motivated. With 61°F. E.T. as a basis of comparison, the amount of deterioration in performance is statistically significant at 83°F. E.T.; when 69°F. E.T. is the base, the deterioration is significant at 87.5°F. E.T.

The design of this experiment permitted Mackworth to examine the role played by incentives during varying conditions of stress. The average work output was 83.1 units for all the test sessions in which the men were strongly motivated and 52.4 units for those in which they were less motivated, an increase of 58 percent due to the incentive. A further analysis was made to determine the relation between the men's competence on the task and the degree of incentive. For this purpose, the men were ranked in order of ability on the test as shown by their scores at the two lowest temperatures. The best 15 men were considered to be "good" and the other 15 were considered to be "average". Figure 10 shows the work output of the good and average men under the two conditions of incentives. The following observations may be made: (1) while a high incentive is always associated with a greater work output both for good and average subjects, the improvement due to high incentive becomes less as the degree of heat is increased; (2) as heat increases, the work output of the

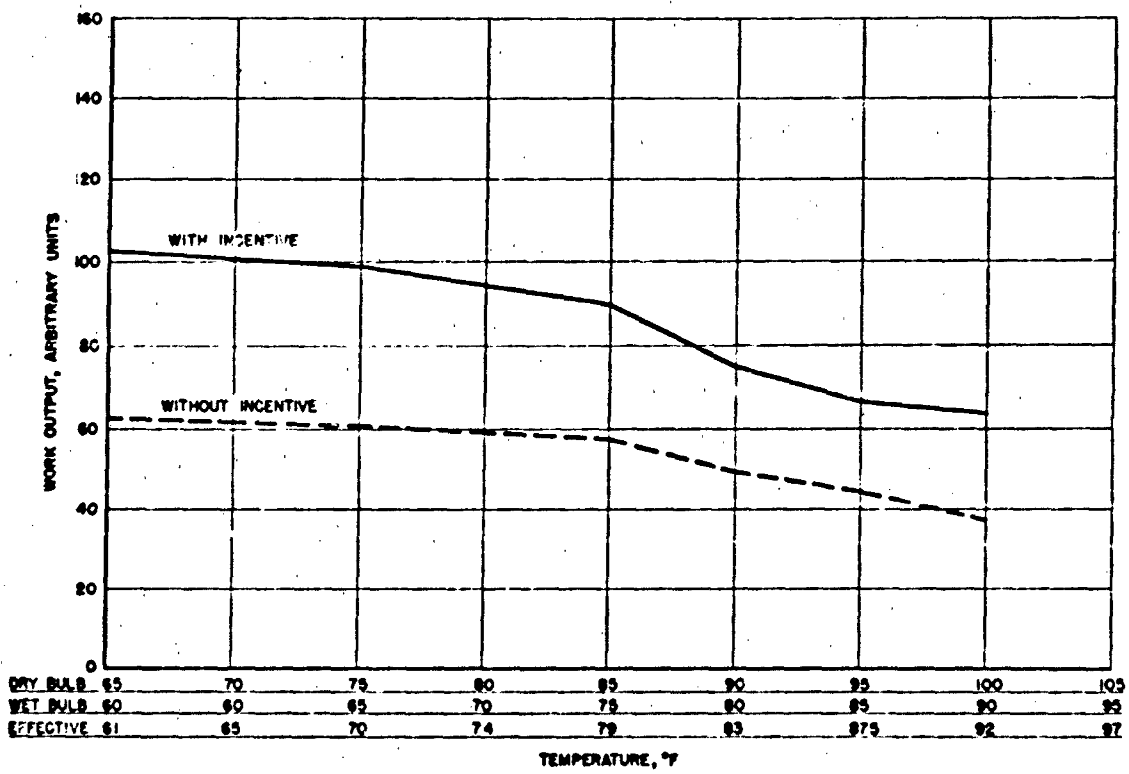

FIGURE 9 AVERAGE WORK DONE IN LIFTING A 15 LB. WEIGHT, IN ARBITRARY ABSOLUTE UNITS, BY 30 MEN UNDER DIFFERENT INCENTIVES IN THE HEAT. DATA FROM MACKWORTH (63)

good subjects, both with high and low incentive, decreases more markedly than does that of the average subjects; (3) as heat increases, the work output of the highly motivated men, both with good and average subjects, decreases more than does that of the less motivated men. In this experiment, all groups of subjects showed some decrement of performance as the degree of heat increased. The greatest deterioration was shown by the good subjects with high incentive, followed by the good subjects with low incentive; still less deterioration was shown by the average subjects with high incentive while the least deterioration was shown by the average subjects with low incentive.

A performance on almost any task reflects both the willingness and the capacity of the subject to perform. It becomes difficult, therefore, to determine in an experiment whether an impaired performance in the presence of stress is a function of reduced willingness or of reduced capacity to perform. Because heat tends to distract an individual, it has been suggested that one of its psychological effects is to reduce motivation. This may well be the case, but the findings in Mackworth's experiment support the view that heat reduces the subject's willingness to perform at the same time that his capacity to perform is being impaired. This study has shown that the largest decrement of performance is suffered by those men who at the outset were more competent as well as more highly motivated. While it would be premature to identify the complex performance of a pilot with the relatively simple task of lifting weights, further study of pilot performance under heat stress may well employ this type of experimental design.

There is an apparent inconsistency between the findings on the Morse code test that the "exceptional" operators deteriorate less than do those who are merely "competent" and on the weight pulling test that the good subjects deteriorate more than do the average ones. It is resolved readily enough if one

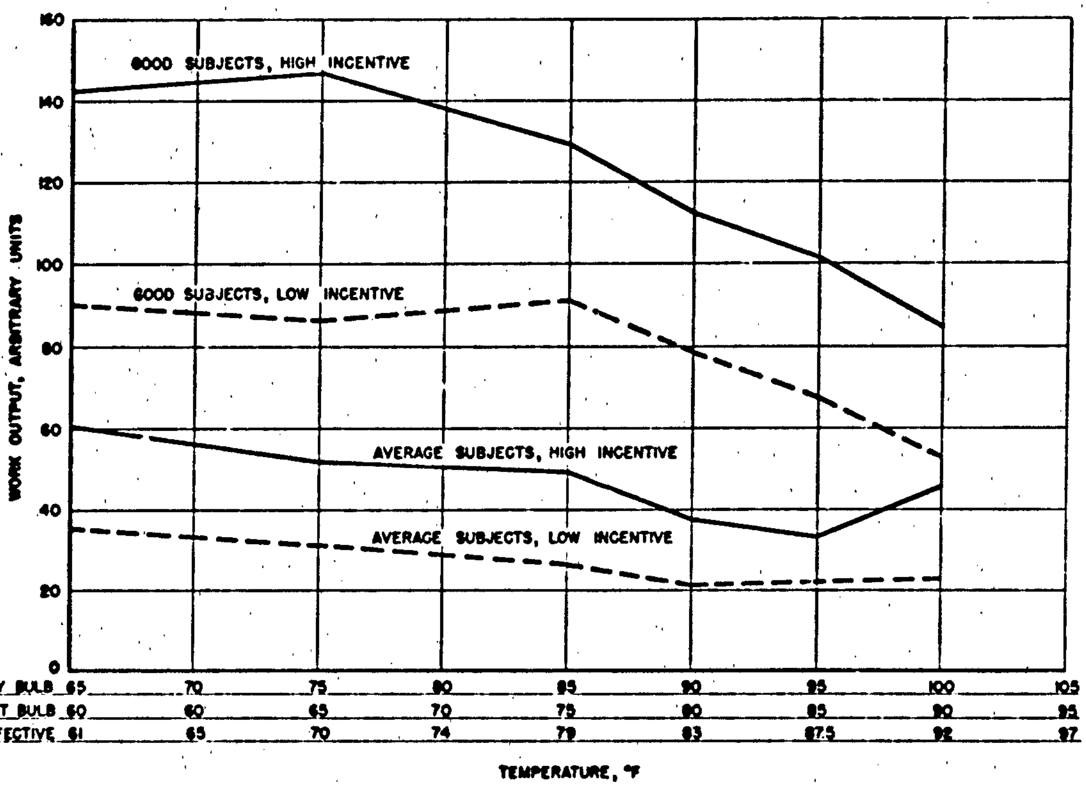

FIGURE 10 AVERAGE WORK DONE IN LIFTING A 15 LB. WEIGHT, IN ARBITRARY ABSOLUTE UNITS, BY 15 GOOD AND 15 AVERAGE SUBJECTS, UNDER DIFFERENT INCENTIVES IN THE HEAT. DATA FROM MACKWORTH (63).

supposes that the factors of motivation and capacity are both involved. According to this supposition, good subjects who have been working close to their maximum capacity will show deterioration in the heat, whereas those who previously have not been working at their maximum capacity can work a little harder in the heat and thus appear not to be affected. While this is a plausible explanation of the disparity between the two experiments, further scrutiny of this point appears to be indicated.

In a recent summary of his work, Mackworth (65) comments briefly on experiments in the heat with two other measures. A block coding test was used to measure the effect of heat on a task which involved moderately difficult problems. Small flat squares had to be arranged on a board according to a series of coded instructions. Twelve acclimatized men showed the following average errors at various effective temperatures (as estimated from a graph):

Effective temperature, °F.	Average errors per series
79	21
83	22
87.5	28.5
92	34
97	43

There is a statistically significant increase in errors at 87.5°F. E.T. as compared with 79°F. or 83°F. E.T.

In a preliminary experiment on the effect of high temperatures on restlessness during sleep, six men slept at night for two weeks in a room at 79°F. and two weeks at 87.5°F. E.T. The days were spent outdoors in the ambient temperatures normal for Britain during autumn and winter. A measure of restlessness was the recorded number of movements per subject for the period from midnight to 7 A.M. There was an increase of 50 percent, found to be statistically significant, from the number of movements at 79°F. to those at 87.5°F. E.T.

Taking all of Mackworth's studies together, one may conclude that

some performance on each task was possible for the duration of the test (2 to 3 hours) up to the highest temperatures tested. However, there were varying degrees of impairment on the several tasks, probably related to the nature of the task, the magnitude of work load, motivation, and the general level of competence of the subjects. Using performance at the lowest temperatures as a base value, one can see that the percentage of errors at the highest temperatures increased by approximately 7 percent on an attention task (visual attention test), 62 percent on a speed and accuracy task (Morse code reception), 17 percent on a light and 20 percent on a heavier motor task (pursuitmeter), 39 percent on the weight pulling task, and 105 percent on the block code test. The large increase of errors on the speed and accuracy task, upon exposure to heat, appears due to the unusual deterioration shown by the less experienced Morse code operators. A numerical comparison of the degree of loss on the several tests cannot be made with the present data because the different error scales have not been equated. Some impairment in performance is demonstrable at such temperatures as 79°F. and 83°F. E.T., but the extent of loss is not statistically significant until an effective temperature of 87.5°F. is reached for the visual attention, weight pulling, and block coding tests and 92°F. E.T. for the Morse code and pursuitmeter tests. The effect of high temperature in reducing output appears greater upon individuals who, because of a high degree of motivation, have been working closer to the limit of their capacity. Performance on a task which requires a large physical effort is likely to be impaired more in the presence of heat than performance on a similar task which requires a lesser physical effort.

6. Bicycling. The ability to maintain an imposed rhythm on a bicycle ergometer was found to drop off considerably at 104°F., 50 percent relative humidity, as contrasted with performance at 68°F., 50 percent relative humidity.

Rate of breathing was increased at the higher temperature, and it took longer to return to normal after work at the higher temperature (57).

7. Weight Lifting. Men were required to lift a 5 lb dumbbell a distance of 2.5 feet at temperatures of 68°F. and 75°F., under conditions of fresh or stagnant air at each temperature (105). They were paid a bonus for the amount of work performed. There was a drop in performance of 14.7 percent due to the increased temperature and of 8.8 percent due to the stagnant air. The greatest loss in output, of about 24 percent, occurred in the combined condition of higher temperature and stagnant air. It may be recalled, in this connection, that Mackworth's data on weight pulling, previously reported, also showed a decrease in performance with heat on a similar task.

8. Motor Coordination. In a study of psychomotor performance, Weiner (93) used a perforated disk which was rotated at constant speed, 84 steel ball-bearings of 3/8 inch diameter, and a forceps. The test required the subjects to pick up the balls by means of the forceps from an inner series of holes, place them as quickly as possible in an outer series, and finally replace them in the inner series of holes. All balls must be in place to complete the test.

Four subjects practiced the test for three weeks, but were not acclimatized to heat. After a two hour exposure to 91°F. E.T. (95°F. dry bulb, 90°F. wet bulb, 30 ft/minute air movement), the average time to complete the test increased by 8 percent over control tests at ordinary room temperature (65° to 68°F., dry bulb). There was no appreciable change in rectal temperature. Another group of six subjects practiced on the test and were acclimatized to heat. In addition, they worked in the heat by climbing on a 12-inch block 24 times per minute for 20 minutes, with a pause of 5 minutes after the first ten minutes. The psychomotor test was conducted in the heat an hour after the

work was completed, at which time pulse rate was steady and rectal temperature was about 101°F. The men required an increase of 14 percent over the control time to complete the test. There was no significant difference between the means of performances in ordinary room temperature, whether or not exercise was carried out prior to the tests. Accuracy was reduced in the heat, as judged by an increase of 32 percent in the number of balls dropped. Again, the accuracy of the performance at normal room temperature was the same whether or not there had been previous exercise. Hand movements in the heat were slower by 6 percent for the time to move each ball, a difference not due to exercise in the normal room temperature tests. All the differences due to the effect of heat-and-exercise are statistically significant.

In another part of the experiment, a single, nude subject lived continuously for 13 days at effective temperatures of 82°F. to 95°F. This subject showed in the hot room an increase of 13.2 percent in the test time on the first 4 days but an increase of only 4.3 percent on the last 6 days. The mean number of errors (balls dropped) decreased constantly, showing the effect of learning and acclimatization; but the mean time per movement, which was at first prolonged from 1.11 to 1.28 seconds, decreased with acclimatization to 1.19 seconds. It would appear, therefore, that all subjects exposed to heat showed a deterioration in performance as expressed in slower movements and more inaccurate handling of the balls; this deterioration is somewhat, but not entirely, reduced with acclimatization.

9. Psychomotor and Other Tests.

a. Pace et al. (73) exposed two groups of six men each to a tropical environment (dry bulb 90°F., wet bulb 83°F., relative humidity 75 percent, effective temperature 85°F.) for nine hours daily. Both groups also spent three hours each day performing treadmill work tests in a hot environment (dry

bulb 108°F., wet bulb 83°F., relative humidity 35 percent, effective temperature 90°F.). In fact, the experimental and control groups were given identical treatment except that the experimental group remained in the tropical environment for 12 hours at night, while the control group returned to a cool environment. Thus, at the times during which measurements were made and work was performed, the two groups were in the same environment. These exposures continued for 30 days, being both preceded and followed by control periods of six days each in the cool environment (dry bulb 80°F., wet bulb 90°F., relative humidity 61 percent, effective temperature 75°F.).

A wide variety of physiological and psychological measurements were made, but attention will be restricted to the latter. The psychomotor tests employed and the general tenor of the results may be seen in the following listing:

A. Tests showing general superiority of experimental group (hot environment at night)

   1. Reaction Time, Complex Visual

   2. Reaction Time, Two-choice Visual

B. Tests showing occasional superiority of experimental group

   1. Critical Flicker Frequency

   2. Limits of the "Red" Visual Field, using Ferree-Rand visual perimeter

C. Tests showing general superiority of control group (cool environment at night)

   None

D. Tests showing occasional superiority of control group

   1. Body sway in a four-minute period (eyes open two minutes, then closed two minutes)

   2. Complex tapping

E. Tests showing no reliable differences between the groups

1. Johnson Code Test, identifying letters according to various code rules

2. Computation Test, three-digit mixed addition and subtraction problems

3. Dark Adaptation, Navy Radium Plaque Adaptometer*

4. Hand Dynamometer, measuring strength of grip

5. Kearth Pursuit Rotor Test, stylus on a moving target

6. Reaction Time, Auditory

7. Hand-Arm steadiness.

The two visual reaction time tests listed under "A" in this outline as showing the general superiority of men continuously exposed to a "hot" environment might suggest that raised temperature increases the speed of visual responses. The tests listed under "B" would tend to support the suggestion. However, it must be pointed out that in the case of the "A" tests there was some indication of an initial difference in favor of the experimental group and this difference became statistically significant during the course of the study and remained so to the end. This observation points o an inherent limitation in the design of the study. One of the requirements for a demonstration of the effects of the imposed difference in environment is that the experimental and control groups must be equated with respect to the characteristic prior to the experiment. If more than one characteristic is to be measured, the principle

*According to the minutes of a conference on "Working Efficiency and High Temperature", held 23 October 1945 (6), Canadian studies have shown that heat during a stay in the Caribbean area impaired dark adaptation. The finding under such conditions is open to question because prolonged exposure to bright sunlight, rather than exposure to heat *per se*, may impair dark adaptation, as shown by Hecht (42). In addition, Clark (18) has reported that prolonged exposure of one eye to sunlight in a hot climate impairs dark adaptation only in the exposed eye.

applies to each of them. When there are 13 tests plus a number of physiological measures, as in this study, it is exceedingly difficult to obtain adequate matching for every test. An initial difference between the groups, though too small to be statistically reliable, may become reliable as a result of stabilization of the subjects' performances. The performance of each subject becomes less variable with practice: the standard deviation diminishes and this serves to increase the statistical reliability of any observed difference between the groups. Thus, the suggestion of a beneficial effect of high temperature must be questioned for lack of adequate evidence.

The tests listed under "B" and "D" led to significant differences favoring one group or the other on one or more days of the experiment. The differences, however, were not found regularly. An overall summary of the psychological tests suggests that no striking difference in performance is demonstrated between the two groups on a series of simple tasks. This inference is in line with the usual findings for conditions of moderate stress. Bartlett (6), for example, has noted that measures of simple performance rarely provide an index of capacity for breakdown under any except the most extreme conditions. This observation was often made in examining the effect of anoxia upon human performance. As evidence that Pace's "hot" environment did entail some stress for the subjects, it may be noted that the prolonged exposure to heat produced a heat rash, whereas this rash did not appear on the subjects of the control group.

b. Birren et al. (11) gave three tests of performance to 40 men on a battleship during a cruise into a tropical area. The ambient temperatures averaged 76.5°F. E.T. on the bridge of the ship and ranged up to 83°F. E.T. at some of the work stations inside of the ship. The experimental group was berthed at night in air-cooled compartments where the mean temperature was 76.2°F. E.T.

while the control group was berthed in ordinarily ventilated compartments where the mean temperature was 83.6°F. E.T. The highest mean effective temperatures reached for any eight-hour period were 80.5°F. E.T. and 87°F. E.T., respectively, for the two groups. The following tests were given before and after the cruise:

(1) Step-up test - The subject was required to step up and down on a bench 18 inches high at a fixed rate until he could no longer continue. Measures were taken of endurance time, cardio-vascular response, and pulse while standing before and after exercise.

(2) Strength of grip - A hand dynamometer was pulled at increments of three kilograms every three seconds. The score was the mean of the highest level pulled by right and left hands.

(3) Johnson code test - The subjects unscrambled a series of letters according to a prearranged code. There were ten trials of one and one-half minutes each, scored in terms of speed.

The speed of decoding increased in the experimental group and decreased in the control group, the total difference between the two groups being about nine percent of the original performance level. The magnitude of the difference approached statistical significance (P equals two to five percent). None of the differences on the other tests was significant.

c. Viteles and Smith (91) used a battery of seven psychological tests to study the performance of six young men exposed to three levels of heat

over a period of seven weeks. The men were selected from among 40 candidates to provide a homogeneous group meeting the physical and psychological qualifications for acceptance by the Navy. Table III indicates the atmospheric conditions examined. Only scanty information was collected at the most severe level. Also, three noise levels (72, 80, and 90 decibels) were employed systematically throughout the tests; but, as has been noted previously in this paper, noise introduced only a slight adverse effect which was unrelated to temperature.

TABLE III

The Temperature Conditions Employed by Viteles and Smith (91)

Effective Temperature	Degrees Fahrenheit Dry bulb	Wet bulb	Percent Relative Humidity
73	70	65.5	79
80	88	73.3	75
87	98	81.5	50
94	108.5	90.5	50

The following performance tasks were used:

a. <u>Mental multiplication test</u> - Problems requiring multiplication of a three-digit and a two-digit number. Performance time was one-half hour, and the test was scored by determining the number of correct digits in the answers.

b. <u>Number checking test</u> - Pairs of numbers to be examined and checked when identical.

c. <u>Lathe test</u> - Two control handles, similar to those found on lathes for moving the cutting tool, are used to trace a circular pattern with an electrified stylus. An error is recorded each time the stylus leaves the pattern while a correct response consists of

tracing one-sixth of the circle without error. The test continued for one hour.

d. Typewriting code test - A sheet with ten different letters arranged randomly in long rows was inserted on a special typewriter but a shield on the roller made it possible to see only one letter at a time. The ten keys in the top row of the typewriter were pressed to make responses according to a given code. Test time was one-half hour.

e. Discrimeter - The subject kept the four fingers of his right hand on four keys, and pressed the correct one according to a number which appeared in a small window. The score was the number of correct responses in one-half an hour.

f. Locations test - A large square, with letters arranged in definite rows and columns, provided the code. Smaller squares, with dots in the same relative position as some letter on the large square, were given to the subject. The subject filled in the corresponding letter as shown on the large, code square. Test time was one-half hour.

f. Pursuit test - Intertwined lines had to be traced by eye from their origin at the left to a block at the right, and identified by a number. Test time was one-half hour.

The subjects were given pre-test practice in these tasks on four consecutive days during which the effective temperatures were held, respectively, at 73°, 73°, 80°, and 87°F. The subjects spent four hours in the heat each day of the tests and, in addition, 90 minutes at rest before the tests and 30 minutes after the tests while control pulse rates and oral temperatures were taken.

Performance on the different tests was computed in terms of output (the total number of work units performed without respect to error), error ratios (total number of errors divided by total output), and variation percentages (the fluctuation in output among successive five minute intervals of the work period, expressed as percentages). Table IV presents the performance output for the different effective temperatures. Maximum output on each of the individual tests was found at either 73°F. or 80°F. E.T., the differences between these two conditions being slight and not statistically significant. The lowest output on all the tests occurred at 87°F. E.T., the reduction ranging from 2.7 to 13.9 percent of maximum output. This reduction in output is statistically significant on the four tests marked with an asterisk in Table IV. There was no reduction in accuracy of performance with

TABLE IV

Group Total Performance Output at Various Effective Temperature Levels
Data from Viteles and Smith (91)

Group Output (Percent of Maximum)

Performance	73° ET	80° ET	87° ET
Mental multiplication	100.0	99.1	96.7*
Number checking	100.0	99.6	95.0*
Lathe	98.5	100.0	86.1*
Typewriting code	100.0	98.1	96.5
Discrimeter	100.0	98.0	97.3
Locations	99.0	100.0	97.2
Pursuit	98.1	100.0	96.5*

*Statistically reliable decrease in performance output.

the increase of temperature to 87°F. E.T. on any of the tests, except for the Lathe test where the loss of accuracy was not statistically significant. There was also a tendency toward greater fluctuation in the amount of work done in successive five-minute periods at 87°F. E.T. than in the milder environments. However, the absolute difference was not large on any of the tests, and it was statistically significant only on the Number checking and Discrimeter tests. In agreement with the subjective comments reported in other experiments, all the present subjects reported unfavorable personal reactions such as feelings of discomfort, sluggishness, irritability, and fatigue, and these were much more marked at 87°F. E.T. than at the milder conditions where no loss of performance occurred.

Only one session was undertaken at 94°F. E.T., and insufficient data were collected to permit quantitative evaluation. None of the subjects was able to complete the task during his first exposure to 94°F. E.T., and all reported such effects as dizziness, partial or complete visual blackout, and nausea. Compared to 80°F. E.T., there was a reduction in output that varied from 14 to 42.6 percent for the different tasks. This study demonstrates significant impairment of performance at 87°F. E.T. and a profound disturbance at 94°F. E.T. The tests employed do not impose a large work load, and acclimatization up to 87°F. E.T. was permitted.

d. Critical Flicker Frequency. Dobriakova (24), in a Russian language report read only in an English summary, studied the effect of warmth on the critical flicker frequency of lights of several colors. Warmth raises the critical flicker frequency in the case of the orange-red and lowers it in the green-blue portion of the spectrum, the yellow region being unaffected. This is another of the inter-sensory effects occasionally reported by Russian investigators. Some of these effects have proved difficult for American

laboratories to confirm. Pace (73) used a red neon light in his test reported above and found that subjects who were exposed continuously to the heat exhibited a higher critical flicker frequency than subjects who were exposed only intermittently. The critical flicker frequency test was administered under the same conditions of temperature for both groups in Pace's study. Dobriakova's report would appear to be consistent with that of Pace. However, the two reports cannot be compared any further because few of the details in the former experiment (as, for example, the degree of "warmth") are available at present.

e. Estimates of Rates and Durations. François (31) used diathermy to obtain an increase of internal temperature in his subjects, who were required to tap at a rate they thought corresponded to three per second. There was an increase of 1.13 percent in the number of taps per second in response to these instructions for every tenth of a degree centigrade increase in body temperature. Increases of pulse rate were not related to the increase of tapping. The finding is confirmed by Hoagland and Perkins (47), who studied subjects with high body temperature due to fever as well as to diathermy. The subjects were asked to count to 60 at a rate they believed to be one per second. The counting was found to be faster at the higher temperatures. These findings suggest the possibility that some judgments involving time may be subject to error when body temperature is raised.

f. Personality. Many passing comments have been made by observers on the psychological effects of heat on the personality of individuals exposed to heat. Information of this sort appears often in reports on tropical medicine, and generally takes the form of indicating that lethargy, loss of motivation, and deterioration of personality occur in tropical climates. Such remarks generally represent the author's impressions and are not based upon the collection of objective test data. A typical instance of this kind of report

is by Sams (82), who says: "After some months of exposure (to a tropical climate) the development of these changes in the blood count and in the blood pressure results in the appearance of certain symptoms...which might be expected with cerebral anemia or arteriosclerosis. The individuals become very irritable, they quarrel and fight over the slightest imagined insult; they become extremely forgetful, and I have seen individuals start out to see someone and forget whom they are going to see...It becomes almost a rule that you must write down everything in a notebook if you are to remember it longer than five minutes. Accompanying this irritability and forgetfulness, the inability to concentrate on a problem becomes very marked. Men complain that they are unable to do their work because they can't concentrate on it. There is nothing particularly new in this syndrome. However, few doctors recognize it as a clinical entity". Without warrant of supporting data, Adolph (100) says that "heat constitutes a severe stress that impairs judgment as well as accomplishment". So far as can be determined, controlled measurements of personality change have not been made during high temperature stress.

While there can be little doubt that high temperature, as in the case of fever, may influence personality, it appears that the existing information is based upon general observation and inference rather than upon experimental investigation. It is to be regretted that objective information is not available concerning the effect of heat upon personality, and it is strongly recommended that such investigation be undertaken. Attention should be directed not only at the extreme conditions where personality disorganization undoubtedly occurs (see, for example, Eichna's study below), but at less extreme conditions as well. Prolonged exposure to moderate heat may constitute a stress upon personality with an effect shown, for example, in the breakdown of co-operation among crew members on long flights.

* * * * * *

The results of the performance studies reviewed in this section are summarized in Table V. Only those tests are listed for which there are quantitative evidence of performance impairment due to heat and a statement of the temperature level at which impairment occurs. With one exception, studies have been excluded unless an estimate can be made of the critical temperature at which impairment may be expected. Two studies of performance under conditions of heat have been excluded from this paper for reasons of security. The findings, however, would not alter the present conclusions.

The first column of figures in Table V shows the highest effective temperature at which performance remained normal, and the second shows the lowest temperature at which deterioration was noted. The deterioration was statistically significant for those values marked by an asterisk. It would be premature to accept the table as indicating the critical temperatures at which all varieties of performance are bound to deteriorate. These studies do not represent an organized survey of the wide range of performances which are possible, and it is certainly not yet clear which, if any, are relevant to the task of piloting an airplane. They are preliminary values, particularly useful for orienting further investigations. They tell us that "normal" performances have been observed at effective temperatures up to 93°F., though generally not above 87°F.; and that deterioration may be noted at 70°F. E.T. on some tasks but not until 92°F. E.T. on others. The wide gap between the temperatures for a "normal" and a deteriorated performance in some studies is due to inadequate experimental design, where only widely separated temperatures were employed. Taking the median as a representative single value, 80°F. E.T. may be suggested as the highest temperature at which many performances are still "normal"; and 87°F. E.T. as the value at which deterioration may be demonstrated on several tasks.

TABLE V

The critical effective temperatures (°F.) at which impairment may be demonstrated, according to various sources.

Name and type of test	Investigator	"Normal" Performance	Demonstrable impairment
Typewriter code (scrambled letters)	Viteles	80	87
Morse code reception	Mackworth	87.5	92*
Locations (spatial relations code)	Viteles	80	87
Block coding (problem solving)	Mackworth	85	87.5*
Mental multiplication (problems)	Viteles	80	87
Number checking (error detection)	Viteles	80	87*
Visual attention (clock test)	Mackworth	79	87.5*
Pursuit (visual maze)	Viteles	80	87*
Reaction time (simple response)	Forlano	93 (1) (2)	-
Discrimeter (complex response)	Viteles	80	87
Lathe (hand coordination)	Viteles	80	87*
Pursuitmeter	Mackworth	87.5	92*
Motor coordination	Weiner	64.5 (2)	91*
Ergograph (weight pulling)	Mackworth	81 (3)	85.3* (3)
Bicycle ergometer (heavy work)	Liberson	64.5 (2)	91.5 (2)
Weight lifting (heavy work)	N.Y. Ventil. Comm.	64.5 (2)	70 (2)

*deterioration statistically significant
(1) provided wet bulb does not exceed 86°F.
(2) effective temperature estimated from data in report
(3) mid-point of a range of conditions

It will be recognized that these preliminary estimates are subject to modification as a wider variety of performances is explored and as the experimental techniques are refined.

As a crude estimate, therefore, of the maximum temperature at which simple sedentary tasks can be undertaken without serious impairment, 85°F. E.T. may be suggested. The only study revealing impairment at a temperature level appreciably below this employed a weight lifting task, and this task implies a work load greater than that for sedentary tasks. Temperatures two or three degrees higher than 85°F. E.T. lead to deterioration on a variety of tasks. Various combinations of dry bulb temperature, humidity, and ventilation which yield the same perceptible warmth as an effective temperature of 85°F. may be estimated from a chart in the appendix of this paper.

The suggestion of 85°F. E.T. as a limiting temperature for normal performance must be carefully qualified in the following ways:

1. Effective temperature implies there are various combinations of temperature, humidity, and ventilation which lead to similar feelings of perceptible warmth. However, none of the performance studies has included a systematic variation of these environmental variables to determine whether or not the same level of performance will be observed in the several combinations which yield the same effective temperature. Mean radiant temperature is often ignored as a variable in these studies. The present status of information permits only the statement that there is a combination of ventilation and of dry and wet bulb temperatures, yielding an effective temperature of, say, 87°F. at which deterioration may be observed. It is not known whether the temperature-humidity-ventilation interrelationships demonstrated for physiological responses (see Sections VI and VII) apply also to performances.

2. The principal criterion of deterioration employed in the studies

referred to in Table V has been a statistically reliable difference between the average performance under heat and some control condition. Deterioration is said to have been demonstrated when performance is measured under two conditions differing only in thermal environment and when the measures in the more extreme environment present an unfavorable comparison with those of the less extreme environment by an amount which exceeds chance or sampling variation. The effects of this magnitude of behavioral deterioration upon successful operation of high speed aircraft are uncertain. The criterion implies that, in general, there will be a handicap in performance specifically attributable to temperature when thermal conditions exceed the critical level for that performance. This handicap may be serious when a man is working near the limits of his capabilities. The imposition of a thermal handicap might be particularly detrimental to those men who are not fortified by extensive training and experience. A reasonable hypothesis is that trangression of the thermal tolerances of performance, as they have been defined above, will increase the frequency and severity of those events and accidents which are often ascribed to "pilot error".

5. As suggested in Section III, performance studies in this field have employed relatively simple tasks; and the effects upon more elaborate activities remain unknown. Piloting a plane often presents situations which are both complicated and complex: complicated in the sense of many contingencies which must guide each movement of the pilot, and complex in the sense that many different operations must proceed simultaneously or in rapid succession. It may be conjectured that the effect of heat may be more pronounced or complex than on simple tasks. In any case it is already clear that exposure to heat results in a definite impairment of performance, the full details of which must be worked out in further experimentation.

VI. Comparison of Tolerances Based on Performance and on Thermal Equilibrium

In Section III, it was suggested that the body may be able to maintain its thermal equilibrium under temperature conditions too extreme for normal performance to occur. In Section V, the available behavioral data were presented and then summarized in terms of the upper limiting thermal conditions under which normal performance can be expected. The purposes of Section VI are: (1) to examine some of the studies in which physiological measures have served as a basis for defining human tolerance of heat and (2) to compare the tolerances based upon physiological measures with the tolerances based upon various performances. Attention is now directed to a group of five relevant studies.

1. Robinson, Turrell, and Gerking (80) conducted 182 series of measurements on men in environments where the dry bulb temperatures ranged from 65° to 123°F., with relative humidities up to 100 percent. Ventilation was constant at 180 feet per minute. Measurements were made of the subjects' heart rates, rectal temperatures, skin temperatures, and rates of sweating; and these were combined into a single value symbolized by "Ep", an overall index of physiological effect.* Robinson determined that men could maintain physiological equilibrium

---

*The equation for E_p is $E_p = E_h + E_s + E_r + E_w$. The values of E_h, E_s, E_r, and E_w are the effects of the environment on heart rate (h), skin temperature (s), rectal temperature (r), and rate of sweating (w), determined according to the general formula:

$$E_x = \frac{(X_3 - X_1)}{(X_2 - X_1)} \cdot 100$$

where X_1 is the base value of heart rate, etc., in a comfortable environment, i. e., 72°F. working, 83°F. resting; X_2 is the value obtained during exposure to most extreme heat, i.e., 123°F.; and X_3 is the value obtained during exposure to the environment being evaluated. Each value of E_x in the index is a ratio, expressing the increment in a particular test condition as a percent of the maximum increment observed at 123°F. The several values are summated equally to yield the overall index, the numerical value of which can range from 0 in a cool environment, i.e., no change, to 400 in severe heat, i.e., 'maximum' change. One of the several assumptions implied in this index is that the four indicators are equally significant.

for 6 hours provided their Ep did not go above 175. Such a value could be produced by moderate work at medium temperatures or by resting at higher temperatures.

Robinson presents a series of figures to show the effect of environment and work load upon physiological stability as expressed in his overall index. Figure 11 reproduces the results for resting conditions. The axes of the figure are wet and dry bulb temperatures, and the values for percent relative humidity appear as a family of oblique straight lines. Upon this grid of horizontal, vertical, and oblique straight lines, Robinson superimposes a series of contour lines with negative slopes to show his findings. The lowest of these is for Ep numerically equal to 50. Every point on this curved line represents equivalent physiological stress as indicated by heart rate, skin temperature, rectal temperature, and sweating. Specifically, his findings imply that a temperature condition of 88°F. dry, 88°F. wet bulb, and 100 percent relative humidity is just as taxing as 99°F. dry, 64°F. wet bulb, and 10 percent relative humidity. Contour lines for larger values of Ep become more nearly vertical to indicate a relative decrease in the importance of dry bulb temperature and a corresponding increase in the importance of wet bulb measures.

A value of 175 for Ep is set as a tolerance limit below which temperature equilibrium is maintained and above which an equilibrium may not be possible. This tolerance limit is about equal to the 93°F. contour on the _effective_ temperature scale. Since the index is the sum of four variables which can add to a maximum of 400, it appears that a tolerable limit is reached when the component measures are, on the average, somewhat less than half way between their normal and their extreme values. If the assumptions of this study are granted and the adequacy of the index is left for physiological evaluation, it appears to be unwise for physiological reasons to carry a man beyond the

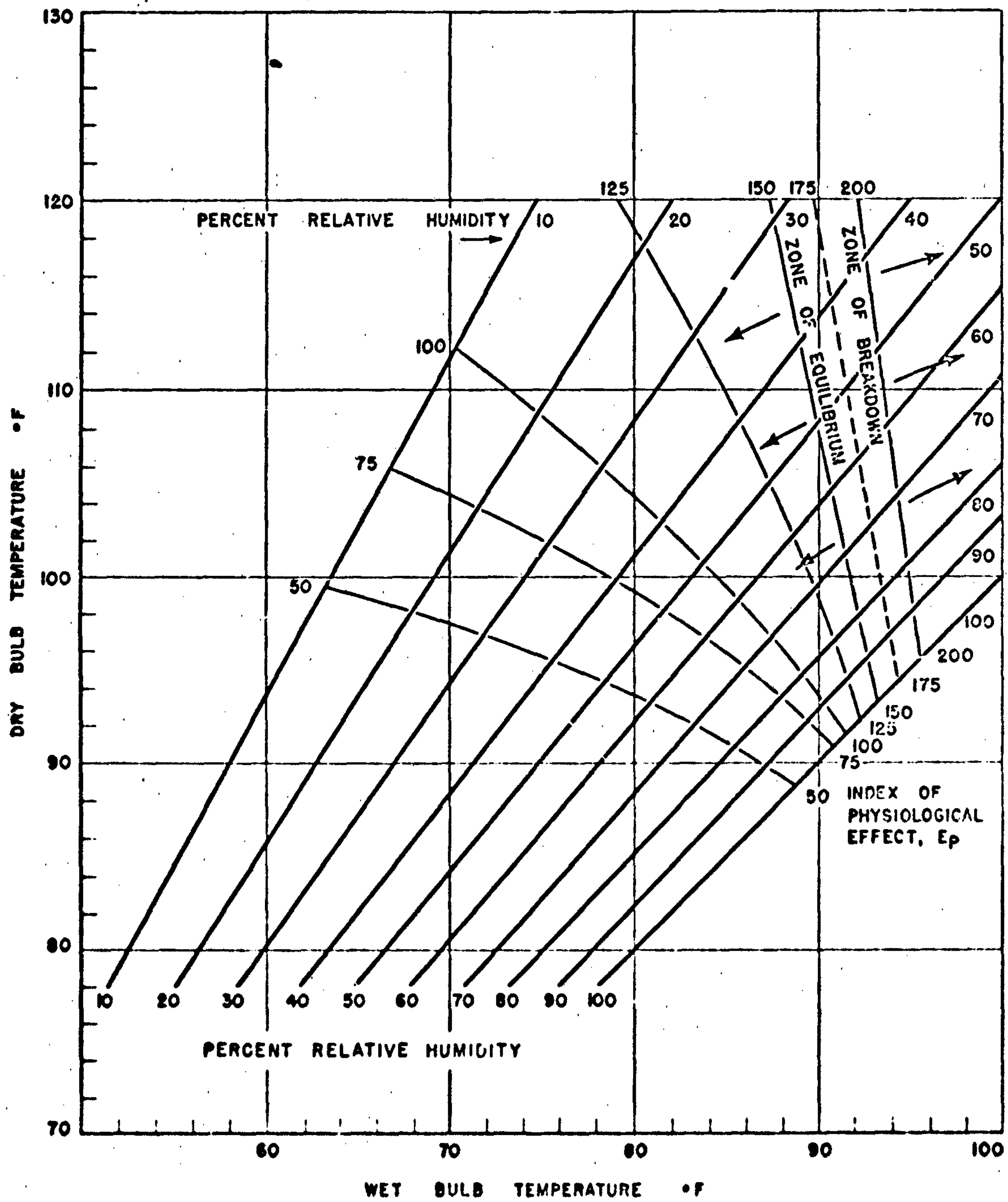

FIGURE 11 THE PHYSIOLOGICAL EFFECT OF THE ENVIRONMENT (E_p) ON 2 MEN WEARING SHORTS SITTING AT REST WITH AIR MOVEMENT AT 180 FT/MIN. (MR 46 CAL/M^2/HR) FROM ROBINSON (80), FIGURE 7.

defined limit. A man carried somewhat beyond Robinson's limit would presumably survive and perhaps be able to carry on some activities for a time, but generally such exposures should be reserved for unusual and heroic circumstances.

Figure 12 is similar in construction to Figure 11 with the difference that the contour lines refer to men who are clothed and are walking at specified speed up an inclined path rather than to men who are wearing shorts and are sitting at rest. As would be expected, all of the contour lines fall nearer the lower left corner of the grid as compared to their position in Figure 11. The upper tolerance line defined as 175 index units has been brought to less extreme temperatures because of the work load imposed upon the subject.

Figure 13 has been developed by collecting several such tolerance lines, each of which refers to a particular combination of clothing and work. The set of conditions most directly applicable to a pilot in a plane is not readily apparent; but, because it is a sedentary task, presumably it falls somewhere between line C and E and perhaps nearer to E.

Robinson's values, of course, refer to physiological stability over a 6 hour period. More extreme conditions can be sustained for a shorter period, as will be shown in Section VII.

2. Robinson and Gerking (78) demonstrated the dependence of man's temperature tolerance upon the amount of heat load due to radiation. The subjects walked on a treadmill while clothed in shorts, shoes and socks, and also when they wore poplin jungle uniforms over the shorts. The tests consisted of walking for two hours at the rate of 3.5 miles per hour on a treadmill with a grade of 2.5 percent. The temperature was 113°F. and the air movement was 180 feet per minute. In addition, the subjects were exposed to radiation from a bank of nine 1500-watt Mazda lamps, set in a reflector, at a distance of 36 inches from the subject. The average radiation striking the subjects was 238

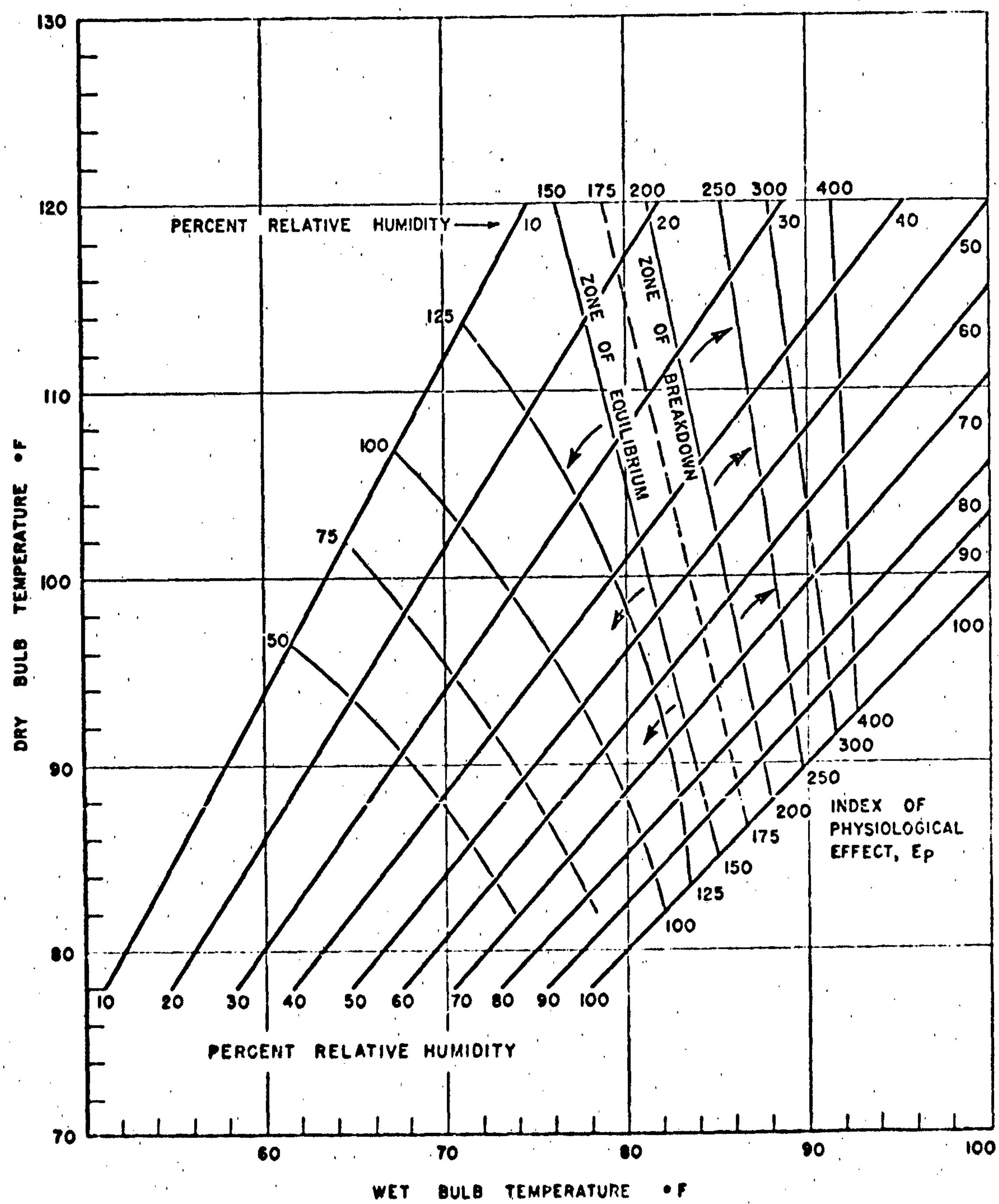

FIGURE 12 THE PHYSIOLOGICAL EFFECT OF THE ENVIRONMENT (E_p, AS DEFINED IN TEXT) ON 2 CLOTHED MEN WALKING AT 3.5 MPH. UP A 2.5 PERCENT GRADE, WITH AIR MOVEMENT AT 180 FT/MIN. (MR 189 CAL/M^2/HR). EACH CONTOUR LINE OF E_p INDICATES CONDITIONS OF ENVIRONMENT WHICH HAD EQUAL EFFECTS ON THE MEN. FROM ROBINSON (80) FIGURE 2.

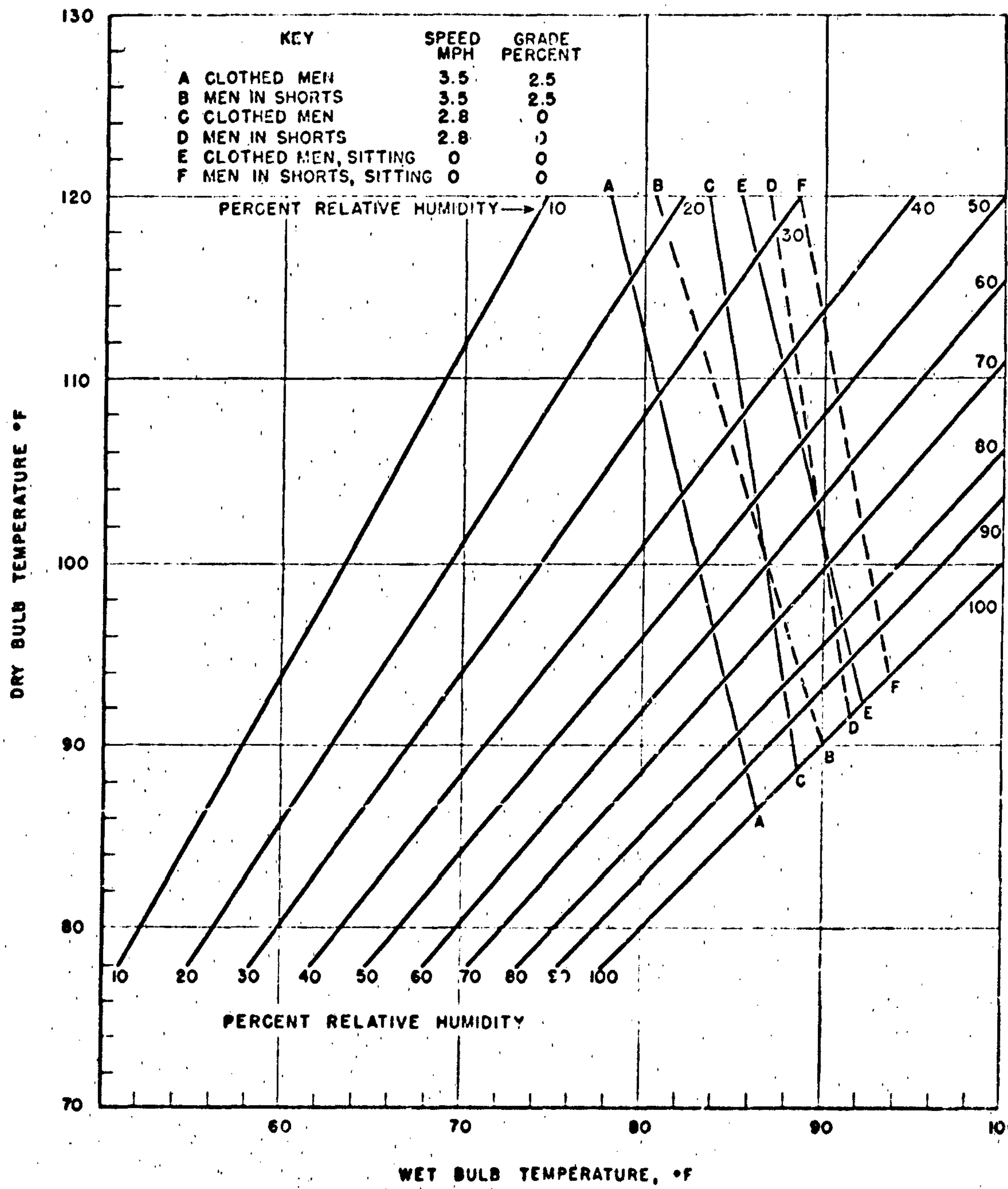

FIGURE 13 THE MOST SEVERE ENVIRONMENTAL CONDITIONS MEN CAN TOLERATE AND STILL MAINTAIN HEAT EQUILIBRIUM FOR 6 HOURS, WITH AIR MOVEMENT AT 180 FT./MIN. THE CONTOUR LINES REPRESENT A VALUE OF E_p EQUAL TO 175 UNDER VARIOUS CONDITIONS OF REST AND WORK.
FROM ROBINSON (80), FIGURE 8.

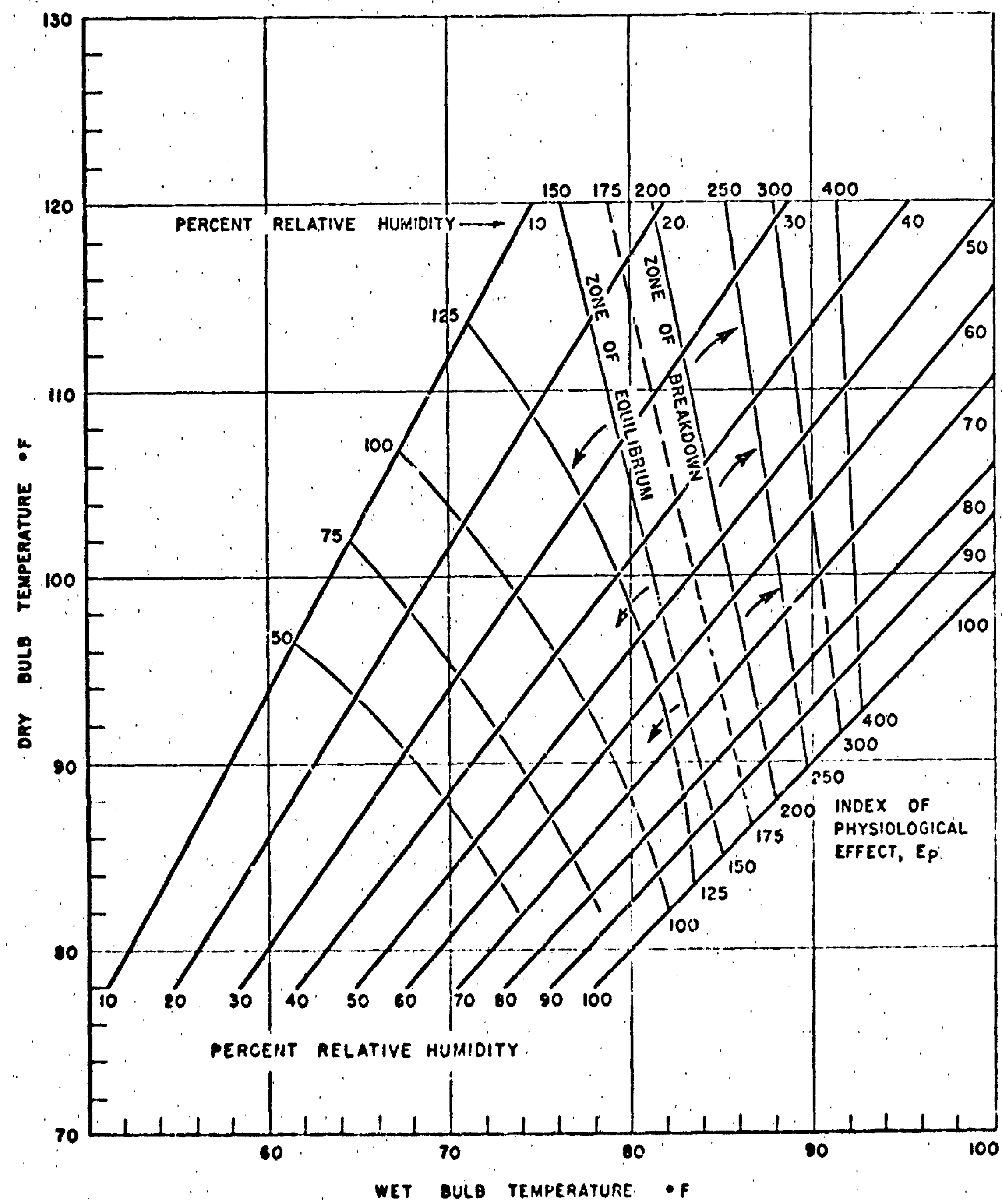

FIGURE 12 THE PHYSIOLOGICAL EFFECT OF THE ENVIRONMENT (E_p, AS DEFINED IN TEXT) ON 2 CLOTHED MEN WALKING AT 3.5 MPH. UP A 2.5 PERCENT GRADE, WITH AIR MOVEMENT AT 180 FT/MIN. (MR 189 CAL/M^2/HR). EACH CONTOUR LINE OF E_p INDICATES CONDITIONS OF ENVIRONMENT WHICH HAD EQUAL EFFECTS ON THE MEN. FROM ROBINSON (80) FIGURE 2.

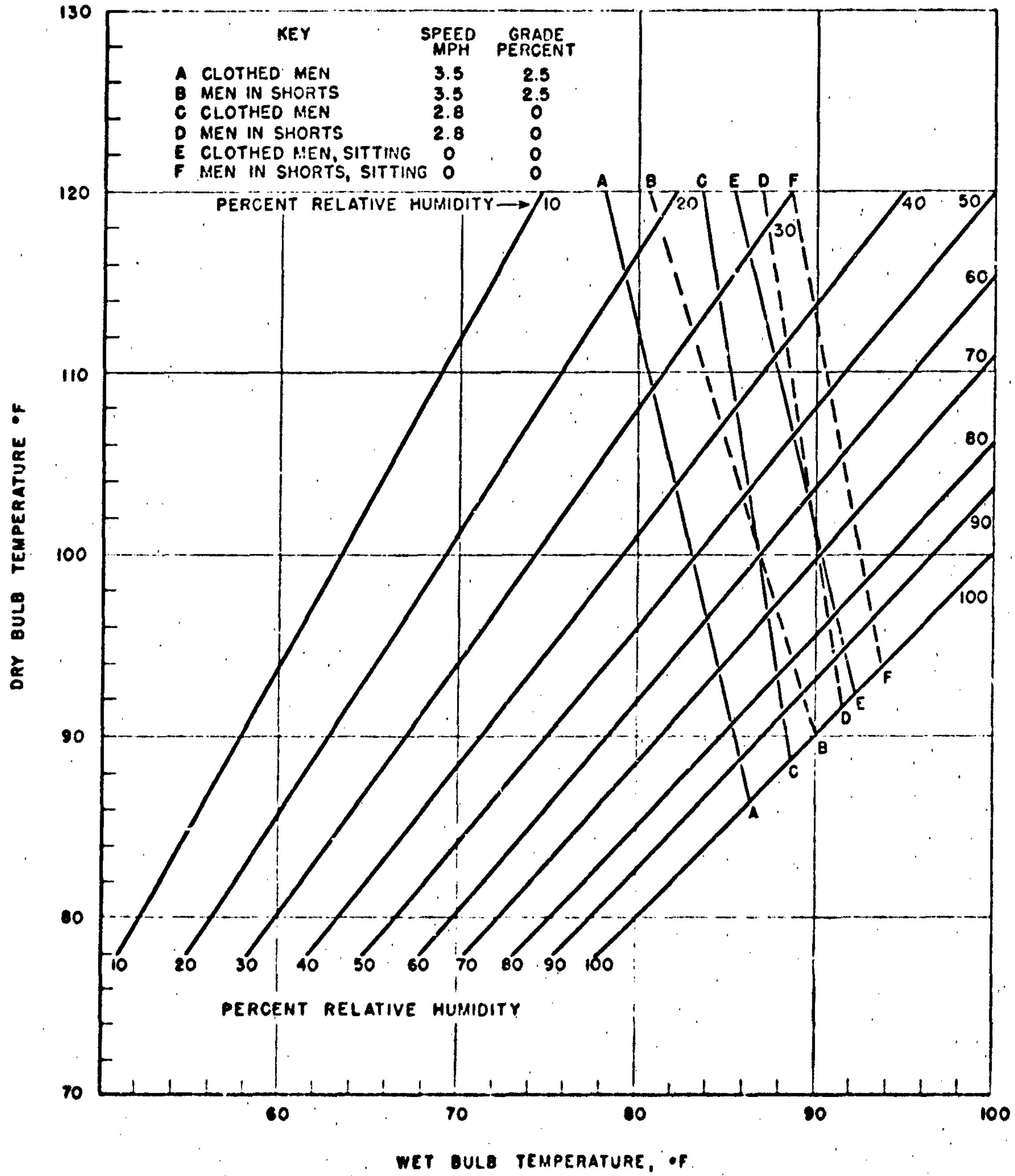

FIGURE 13 THE MOST SEVERE ENVIRONMENTAL CONDITIONS MEN CAN TOLERATE AND STILL MAINTAIN HEAT EQUILIBRIUM FOR 6 HOURS, WITH AIR MOVEMENT AT 180 FT/MIN. THE CONTOUR LINES REPRESENT A VALUE OF E_p EQUAL TO 175 UNDER VARIOUS CONDITIONS OF REST AND WORK.
FROM ROBINSON (80), FIGURE 8.

cal $/m^2/hr.$ when 3 lamps were on; 445 cal $/m^2/hr.$ when 6 lamps were on; and, while the amount for all 9 lamps is not reported, presumably it is of the order of about 700 cal $/m^2/hr.$ There were clear-cut increases of heart rate, skin temperature, and sweating with the increments of radiation. The men completed the tests in all except the most extreme condition. Thus, a task which can be completed in the absence of radiation may become impossible at the same general air temperature when a heat load due to radiation is imposed. This study, which is chronologically prior to the Robinson study reviewed above, amplifies the findings by pointing specifically to the fact that radiational heat load must be taken into account in setting temperature tolerances.

3. Eichna, Ashe, Bean, and Shelley (27) attempted to determine the upper limits of heat and humidity under which men might accomplish useful work. A group of 13 men was acclimatized and then exposed repeatedly to 18 different environments that ranged up to 120°F. dry bulb, 96°F. wet bulb, and 97°F. effective temperature. In each environment, the men were required to march continuously for four hours at three mph on a level surface while carrying 20 lb packs. The men, who varied in age from 18 to 30 years (average 21.6 years), wore no clothing except socks and shoes. Water, slightly salted, was always available and the men were urged to drink it. The men lived in the hot quarters during the day, always marching in the morning; they returned to their barracks each evening. Measurements were made of heart rate, rectal temperature, and respiratory rate during the three-minute rest periods, which were allowed after every hour of work. In addition, records were kept of the amount of water drunk, urine voided, gastric contents vomited, and sweat produced; and, upon completion of each day's work, notations were made of the skin temperatures of the cheek, chest, palm, forearm, thigh, and calf.

The several environments are classified in Table VI as "easy", "difficult",

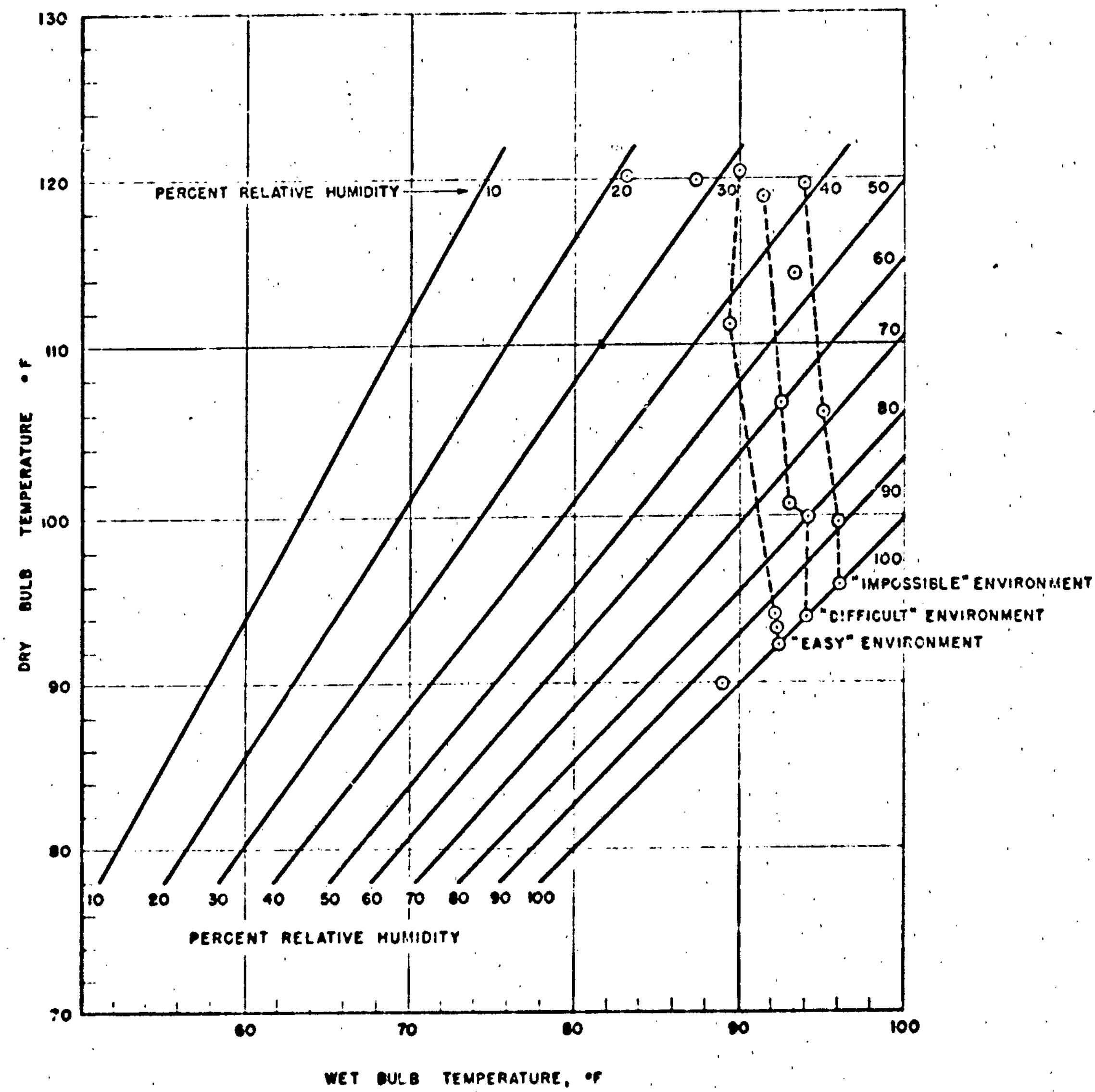

FIGURE 14 AFTER BEING ACCLIMATED, 13 MEN CARRYING 20 LB. PACKS, MARCHED REPEATEDLY FOR 4 HOURS AT 3 MPH. IN 18 DIFFERENT ENVIRONMENTS. THE LINES ON THE FIGURE JOIN THOSE CONDITIONS UNDER WHICH THE WORK WAS "EASY," "DIFFICULT" OR "IMPOSSIBLE". INSUFFICIENT DATA WERE COLLECTED FOR THOSE POINTS WHICH ARE NOT CONNECTED TO LINES. DATA FROM EICHNA (27)

or "impossible" according to the degree of difficulty encountered in completing the task. Examination of the effective temperatures shown in the last column indicates some overlapping between the different levels of difficulty. The overlapping in each case results from a combination of a very high dry bulb temperature with a low humidity, which turns out to be less "difficult" than might be expected from knowing the effective temperature alone. In Figure 14, these environmental conditions are arranged on a psychrometric chart similar to that employed by Robinson, with contour lines that connect the environments which produced similar effects.

TABLE VI

Test Environments Studied by Eichna (27), Arranged According to the Type of Response They Produced on the 13 Subjects

Type of Environment	Dry bulb °F.	Wet bulb °F.	Relative humidity percent	Effective temperature
"easy"	92.6	92.4	100	91.0
	93.3	92.1	95	90.7
	94.1	92.1	93	90.9
	111.6	89.5	43	92.6
	120.6	89.8	30	94.4
"difficult"	94.0	94.0	100	92.8
	100.0	94.2	81	94.1
	100.8	93.0	76	93.1
	103.4	92.5	69	93.7
	119.3	91.7	36	95.6
"impossible"	96.1	95.9	100	95.3
	99.7	96.1	88	95.8
	106.2	95.0	67	95.8
	119.9	93.9	38	97.2
insufficiently studied	90.0	88.8	96	86.8
	114.2	93.1	46	95.6
	120.2	83.1	21	90.6
	120.2	87.6	28	93.1

The men worked readily and without effort in the "easy" environments. All of the men finished four hours of continuous marching and, on its completion, were alert and seemingly capable of continuing the work indefinitely. The physiological changes at the end of four hours were mild and within the range of those previously encountered in acclimatized men working in the desert or tropical heat. Rectal temperatures were 100°F. or less and heart rates 130 per minute or less.

All men were able to march for four hours in the "difficult" environments but with much effort and many complaints. There were frequent requests to discontinue before the end of the period. Some men completed the task only with repeated exhortations, blandishments, and threats. Complaints of headache, fatigue, dizziness, and nausea were common; occasionally, some men vomited. On completing the work, most men were very tired; half of them probably could have continued further, the other half probably not. The physiological changes at the end of four hours were more drastic than those usually encountered in acclimatized men working in desert or tropical heat. Rectal temperatures of 101°F. to 102°F. and heart rates of 130 to 145 per minute were prevalent. However, a few of the men in the group had no greater difficulty in these environments than in the relatively easy ones.

Most men were able to accommodate to the "difficult" environments during the second hour of work. At the end of the first hour, most men looked ill, worked with difficulty, and experienced distressing symptoms. A few vomited, while some requested permission to discontinue. They began to improve toward the end of the second hour. They looked and felt better and complained less. Thereafter, the subjective improvement continued, and they finished four hours of work in fairly good condition. Both the subjects and observers agreed that the men were better at the end of the test than they had been during the second hour.

As a unit, the group never finished more than one hour of marching in the "impossible" environments. The men worked with great effort and had to be goaded continually to maintain the work rate. One-third of the men were able to complete two hours of work and only two men finished four hours of continuous effort. Undesirable symptoms, which appeared after 30 minutes of walking, progressed rapidly and soon most of the men were completely disabled. There were frequent complaints of violent throbbing headache, dizziness, marked fatigue with inability to keep the pace, difficulty in breathing, coronary type of precordial pain and substernal distress, abdominal cramps, and nausea. Men became glassy-eyed, stumbled and swayed, and bumped into the walls. Some men fell into corners of the room, vomiting copiously (as much as 1.5 to 2 liters); others became disoriented and could not read the time correctly or even repeat their serial numbers; still others were "out-on-their-feet" and did not recall what happened until revived several minutes later in an adjoining cool room. A few collapsed outright. The physiological changes were "excessive"; usually the rectal temperatures were over 102°F. and the heart rates exceeded 150 per minute.

Eichna's results, as shown in Table VI, indicate that a narrow range of <u>wet</u> bulb temperature (4°F. to 5°F.) separates environments in which work is relatively easy from those in which work is impossible. Below wet bulb temperatures of 91°F. men work easily, efficiently, and with only mild physiological changes. Between wet bulb temperatures of 91°F. and 94°F., men are capable of prolonged, moderately hard work; but they work inefficiently and with difficulty, lose vigor and alertness, sustain undesirable physiological changes, and may become mild heat casualties. Moderately hard work at wet bulb temperatures greater than 94°F. leads rapidly to total disability with excessive, and often disturbing, physiological changes. Approximately one hour

of sustained work at 94°F. wet bulb is tolerated by most men; those who work longer do so with marked physiological disturbances.

4. Darling (22) reports a study which illustrates how under special conditions tolerances may fall well below those given by Robinson. The results are presented in terms of average tolerance times for 200 enlisted men (100 white and 100 colored) walking out-of-doors at a rate of three mph under sunny conditions in a moderate wind. The men wore impermeable suits, a fact which suggests that for the unexposed areas of the body (1) humidity was effectively very high, (2) air movement was very low, and (3) considerable insulation was afforded by the suits. The tolerances for four different temperatures are given as follows:

Temperature, °F.	Average Tolerance, Minutes
70	100
75	60
80	40
85	25

As a comment on the thermal conductivity of the suits, it was noted that keeping the suits wet, or better, covering them with wet porous cloths, improved performance strikingly. The tolerance time at 86°F., 50 percent relative humidity, was more than doubled by this means.

All of these values fall below Robinson's tolerances even when 100 percent humidity is assumed. Robinson's studies, it will be recalled, involved periods of 6 hours and Eichna's periods were 4 hours, as compared with an average of 100 minutes or less as reported by Darling.

5. Brunt (16) presents a set of heat tolerance contours based upon groups of subjects exposed to increasing degrees of thermal stress, as follows:

A. nude subjects, resting indoors
B. clothed subjects, resting indoors
C. clothed subjects, resting in sunshine
D. clothed subjects, walking 4 mph in sunshine
E. clothed subjects, walking 4 mph in bright sunshine.

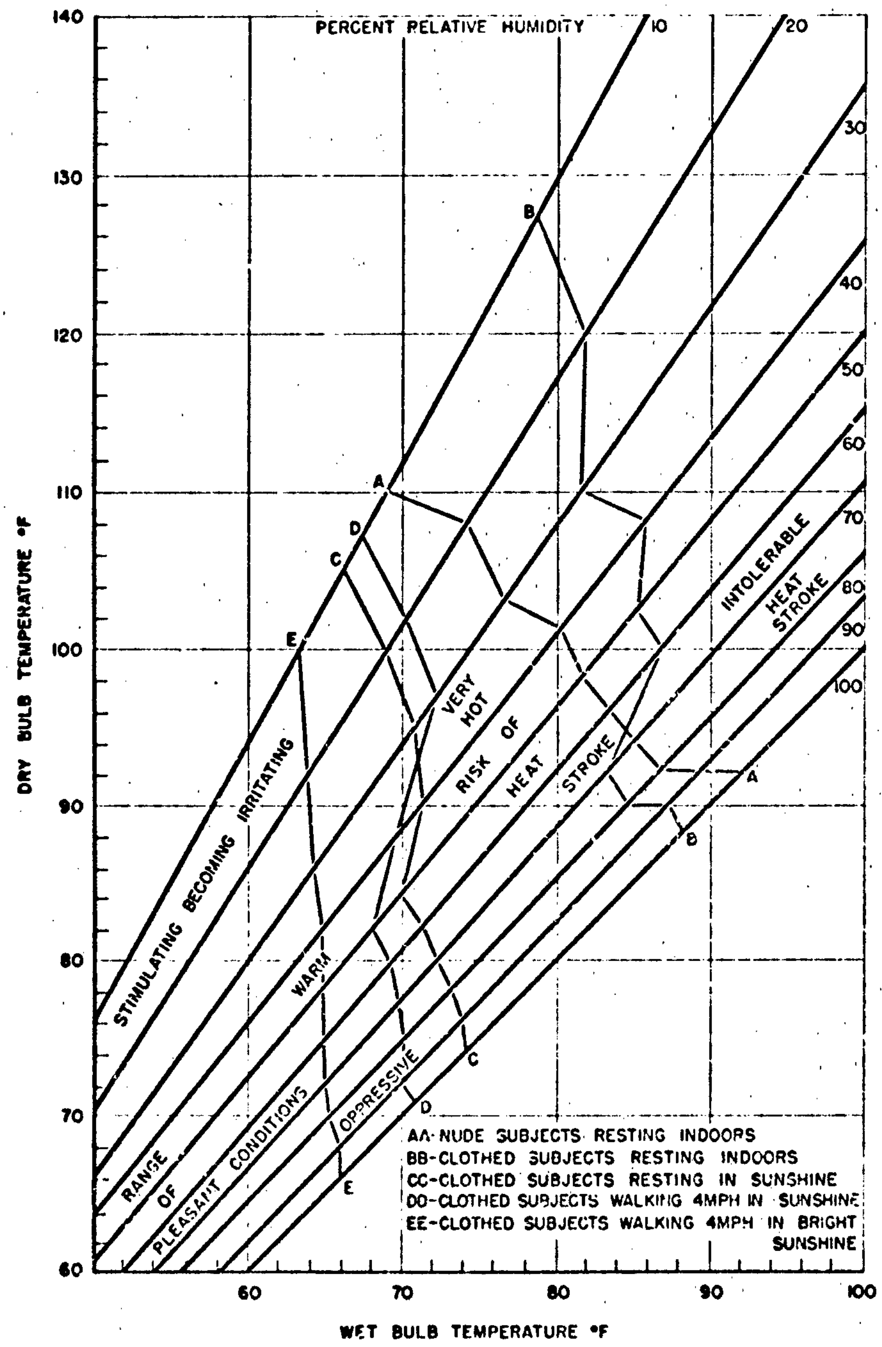

FIGURE 15 THE LIMITS OF TOLERANCE FOR VARYING DEGREES OF ACTIVITY. AFTER BRUNT (16).

A figure presented by Brunt has been redrawn in Figure 15 on the psychrometric scale used by Robinson, in order to facilitate comparison with other reports. The ordinate scale, it will be observed, is enlarged to admit the additional range of dry bulb temperatures covered by Brunt.

Brunt's contours generally fall at much less extreme temperature-humidity conditions than do those of Robinson, as a comparison of Figure 15 with Figure 13 will demonstrate. For example, Brunt's contour AA for nude subjects resting indoors should be roughly comparable to Robinson's contour F for sitting men in shorts. These contours pass through about the same dry bulb temperature (92° and 94°F.) at 100 percent relative humidity. However, at 30 percent relative humidity, Brunt gives 104°F. while Robinson gives 120°F. dry bulb. Likewise, Brunt's BB contour for clothed subjects resting indoors is less extreme than Robinson's comparable E contour for clothed, sitting men. Brunt gives 83°F. dry bulb at 100 percent relative humidity and 110°F. dry bulb at 30 percent relative humidity while Robinson's comparable values are 92°F. and 117°F. Brunt's walking men (contours DD and EE) also yield contours much less extreme than do Robinson's (contours A, B, C or D).

Brunt's contours may be expected consistently to yield a set of temperature values milder than those given by Robinson or Eichna. The explanation undoubtedly lies in the fact that Brunt's tolerance criterion was less severe than that adopted by the other two investigators. Brunt set his tolerances at the highest relative humidity in which body temperature can remain constant in given conditions of air temperature and ventilation. Robinson and Eichna, on the other hand, considered conditions tolerable if the subject would not exceed certain raised physiological levels for a period of 6 hours and 4 hours, respectively.

The five studies just reviewed have yielded a series of tolerance

contours based primarily upon physiological measurements and applicable to different work loads. The studies of Robinson appear to be the most elaborate and complete albeit there are unanswered questions about the nature of the physiological index he uses and the way the constituent measures are combined. His results are not as conservative as Brunt's, nor yet as extreme as Eichna's. Darling's study points out the drastic modifications that special conditions may have upon these tolerances.

When these studies are compared with those described in Section V, the following comments and suggestions emerge:

1. As suggested in Section III and again at the close of Section V, the studies based upon physiological measurement appear in general to be more thoroughly developed than the studies dealing directly with performance. The writers of this review have found no evidence of studies now in progress or contemplated for the next year or two which will serve to round out the performance aspect of the temperature problem. Of the major contributors to the performance studies within the last few years, apparently only Mackworth in England is continuing with such problems. Several temperature research programs are now in progress in this country; and, while they appear to emphasize physiological measurements, they may incorporate performance studies at some later date.

2. The results collected in Table V show that some performances deteriorate under thermal conditions less extreme than those referred to by Robinson, as shown in Figure 13. Specifically, Viteles and Smith found performance impairment on several tests at 98°F. dry bulb and 81.5°F. wet bulb, effective temperature 87.5°F. This point would fall below the lowest contour in Figure 13. Robinson's A line, it may be noted, represents a range of approximately 86°F. to 89.5°F., effective temperature. Thus, men were unable

to exhibit normal test performance under conditions approximately equal to those in which Robinson's clothed subjects, walking at 3.5 mph up a 2.5 percent grade, maintained an Ep of 175. Some of Mackworth's studies reveal impairment at 95°F. dry bulb and 85°F. wet bulb, effective temperature 87°F. This point also falls near Robinson's A line. Figure 11 permits a direct comparison of performance tolerances with Robinson's contours, since this figure is based upon "men wearing shorts sitting at rest". The contour for Ep = 175 includes conditions more extreme than those under which both Mackworth and Viteles and Smith demonstrated deterioration in performance. In fact, the environments studied by Mackworth and Viteles and Smith fall in the vicinity of Ep = 75 and not 175. Evidently the permissible rise of the physiological measures above normal is far greater when thermal "equilibrium" is the requirement than when performance normality serves as criterion. Accordingly, Robinson's tolerances, i.e., acceptable temperatures, are set at such high values that their use for the specification of allowable temperature would permit men to be exposed to conditions in which their activities would be significantly impaired.

Likewise, the contour which Eichna et al. describe as "easy" environments, in which men can march without special difficulty for four hours at three mph, represents conditions where performance on several kinds of psychomotor tasks would be adversely affected. However, Brunt's lines A and B and especially A (Figure 15) pass near the few points representing performance tolerances which have been determined. In this connection, it is interesting to recall that Brunt's criterion was constancy of body temperature.

3. Thus, in the light of present information, there is reason to believe that some of the studies of thermal tolerances based upon elevation of physiological responses, such as heart rate, sweating, and skin and rectal

temperatures, may yield values of limiting temperatures and humidities more extreme than those at which some human performances begin to deteriorate. Consequently the use of such tolerances in the design of airplane cabins is open to question if it is assumed that the pilot must be able to perform in a normal manner. Since the performance tolerances occur at environments as mild as or milder than those for the physiological tolerances examined in this section, there is an urgent need for more performance studies which will give more explicit and detailed information about the limitations that high temperatures place upon a man engaged in sedentary activities. The scarcity of current researches in this particular area should lead to the demand for further investigations. The immediate practical answer to cabin design specifications should be given in terms of the lowest pertinent tolerance. This would appear to indicate performance rather than physiological equilibrium as the critical tolerance. Deterioration of performance by an amount which is statistically significant may be taken to indicate the quality of performance which is no longer acceptable. The degree to which this criterion can be relaxed to meet emergency conditions remains to be determined.

The studies examined thus far have involved relatively long exposures measured in hours. The tolerance of high temperature for shorter periods of exposure will be considered in the following section.

VII. Physiological Limits Imposed by Heat

The researches discussed in this section have been separated from those of the preceding section primarily on the basis of the kind of limit or tolerance studied. In Section VI, interest is directed primarily to the extreme environments in which men can remain active for several hours without serious physiological consequences. In Section VII, the criteria are generally survival or imminent collapse. The first two studies to be considered are census reports of deaths during heat waves. Thereafter several experimental studies will be discussed.

A. Census Studies

1. Schickele (85) reports on 198 cases of heat fatalities suffered by soldiers while training in the U.S. from 1942 to 1944. Cases in which excessive dehydration appeared to be involved and also a few other miscellaneous cases were excluded so that the data would represent deaths clearly ascribable to heat. The age distribution of the 147 remaining men is not given, but they are described as healthy young men who met death while working for several hours at average activity in the sun. Figure 16, reproduced from Schickele's paper, summarizes the conditions of humidity and temperature on the day of onset of these cases of fatal heat stroke. Schickele also gives the formula for a "heat death line" as

$$T = 119 - 2V$$

where T is the dry bulb temperature in degrees Fahrenheit and V is the vapor pressure in millimeters of mercury. This line, which has been superimposed upon Schickele's graph in Figure 16, appears to be arbitrary and serves simply to indicate that all fatalities (except two) occurred under more extreme conditions than those described by the "heat death line". The data do not indicate the size of the total population from which these cases are taken and accordingly

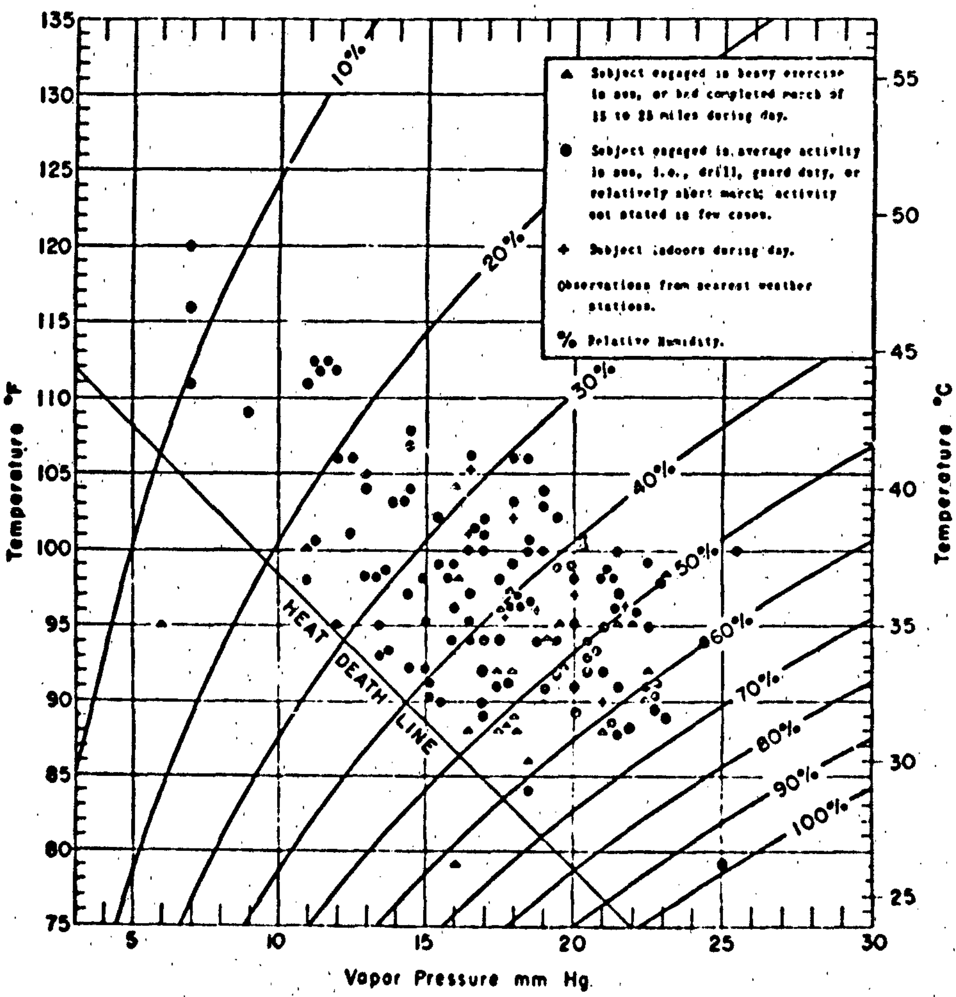

FIGURE 16 HUMIDITY AND MAXIMUM TEMPERATURE ON DAY OF ONSET OF 147 CASES OF FATAL HEAT STROKE IN THE U. S. ARMY. TAKEN FROM SCHICKELE (83).

the expected rate in the Army of deaths due to heat cannot be estimated.

This study indicates that deaths from heat can occur at temperatures as low as 79°F. although very few occur below 88°F. Since less than three percent of the observed cases fall below the latter temperature and evidently the number of deaths is only a minute fraction of the total number of Army men exposed to high temperatures, it may be inferred that heat deaths at ambient temperatures below 88°F. are indeed very rare irrespective of humidity, type of work undertaken, clothing, or temporary physical condition. Thus, as conditions become progressively more severe than those indicated by the "heat death line", the probability of death gradually increases. The cases shown must represent the lower tail of a theoretical cumulative distribution showing the probability of death as a function of temperature and humidity where accessory conditions such as duration, work load, and physical conditions are not controlled. The rather sudden onset of cases just above the "heat death line" may suggest the possibility of occasional, unrecognized heat deaths below Schickele's line. The applicability of results obtained on an Army group to an aircrew population remains to be determined.

2. The frequency of heat deaths in a civilian population subjected to a heat wave is illustrated in a study by Root and Stone (81). They found that 295 deaths due to heat occurred in Detroit when the maximum temperature exceeded 100°F. on seven consecutive days. The relative humidity remained approximately 50 percent. The temperature did not fall below 69°F. and was as high as 104°F. twice during the period. The authors believe that most cases where heat was not a primary cause of death have been excluded from their data. Since a population of 1,500,000 was involved, the overall death rate due to the heat may be estimated as about .02 percent. The distribution of deaths according to age shows that 87 percent of the deaths due to heat occurred among

people 45 years of age and older, and 98 percent among those 50 years and older. The death rates for the different age groups were not given, although they can be estimated from census data.

Thus, in a civilian population a death rate of .02 percent or 2 per 10,000 is found as a result of exposure to temperatures which overlap the lower half of the temperature range noted in the study of Schickele. It would be expected that the rate for a military population would be very much smaller since the deaths in the civilian population involve predominantly individuals above military age. Furthermore, the civilian population includes individuals who are military unacceptable.

The implication of these two studies for performance is that heat, under very rare circumstances, may cause death at 88°F. Interference with performance _can_ occur at even lower temperatures because (1) deaths have been noted at ambient temperatures as low as 79° and (2) performance will be altered under conditions less extreme than those producing death.

B. _Experimental Studies_

One of the important characteristics of the studies reviewed in this section is that the person being tested is not required to engage in any particular activity. No tasks are prescribed and the subject merely sits quietly to endure the period of exposure. Work load and specified performance have been reduced to zero. Under such conditions, duration of exposure remains as one of the principal variables which must be considered when specifying the upper acceptable limits of temperature, humidity, and ventilation.

As would be expected, very high temperatures are tolerable if the duration is made sufficiently short. With duration limited to a fraction of a second, very high temperatures are required to produce flash burns. When the period of exposure is several minutes, the tolerable temperature is lower than for exposures measured in seconds, and yet high as compared with temperatures which

can be tolerated for several hours. There is, for example, a report which may be mentioned here solely for historical reasons. Dr. Charles Blagden is said to have survived in 1775 an eight-minute exposure to 240° - 260°F. As Brunt (16) relates it, Blagden experienced no discomfort for the first seven minutes; but he began to be aware of "rapid distress in breathing" and "a feeling of anxiety" in the last minute.

1. At Wright Field, Taylor (86,87) exposed seated subjects, clothed in underwear and light cotton flying coveralls, to dry bulb temperatures ranging from 90°F. to 166°F. and vapor pressures from 8 to 53 mm Hg. In the main series of observations there were 70 exposures, 60 of which continued for 60 minutes and 10 of which were discontinued after shorter intervals due to imminent collapse of the subject. Physiological effects were measured in terms of heart rate, sweat loss, skin and rectal temperatures; and these indicators were combined into an "Index of physiological response". To facilitate the plotting of contours the "Index" was correlated with the combination of dry bulb temperature and vapor pressure.* This correlation yields the following multiple regression equation between this index and the two environmental variables:

Index = 0.40 x dry bulb temperature, °F. + 0.59 x vapor pressure, mm Hg - 42.3. The procedure for evaluating the physiological effect of any given environment is (1) to enter the dry bulb temperature and humidity expressed as vapor pressure in the above equation and compute the index number. (2) The index number may then be evaluated by reference to the following schema:

Physiological Index Number	Physiological Classification for 30 min. exposure	Physiological Classification for 60 min. exposure
21 or less	tolerable	tolerable
27	tolerable	marginal
33	marginal	intolerable

*See footnote next page.

The criteria for "tolerable", "marginal", and "intolerable" follow. "Tolerable" environments are such that, without prior acclimatization, young men dressed in underwear and flying coveralls and sitting quietly can be exposed for the prescribed time without displaying "symptoms of heat exhaustion, collapse, or any of the extreme sensations which forced subjects to leave intolerable environments". A few of the men placed in "marginal" environments were unable to remain for the entire period. Indirect evidence indicates that most of the men

---

*The use of correlational technique in this study merits special comment. The procedures and formulas of the statistician admit of two very different kinds of use by scientists. On the one hand, the methods may be employed to derive from a collection of observations a test or evidence for a hypothesis. In this case all of the assumptions of the methods must be satisfied and the procedures carried out in conventional manner before the evidence is acceptable. On the other hand, the formulas may be used merely to derive a hypothesis, which will be tested subsequently by independent methods. Taylor's use of correlation technique is clearly of the latter kind, as he carefully points out. When the procedures are used in this manner, it is immaterial whether the assumptions implied by the methods can be defended or not, for the subsequent tests will determine the adequacy of the hypothesis irrespective of how the hypothesis was derived. Taylor's data are such that they cannot satisfy several of the assumptions implicit in zero order, partial and multiple coefficients and he specifically mentions that "intra-individual and inter-individual data are treated together, and the correlations are based on a small number of variates" as examples. This situation should not be permitted to disturb the non-statistically trained reader, provided he accepts the independent physiological validation which the author offers in his "check tests". One danger which accompanies this use of statistical formulas is that, once the manipulations have been accomplished, there may be a temptation to draw statistical inferences from the results. Indeed, some statisticians may question an occasional inference of the author which is based on the magnitude of zero order or partial coefficients. Nevertheless, such inferences do not offset the major conclusions of the study.

The theoretical position of the author is precisely the same as it would be if he had proceeded as follows: (1) Let some kind of line be drawn through a graph in which the variables are dry bulb temperature and vapor pressure. (2) The varied environments represented by points along this line are examined to determine (a) whether they produce similar effects upon man and (b) whether these environments are critical in the sense of just avoiding heat collapses of the subjects. If conditions (a) and (b) are satisfied, the line is a heat tolerance contour. (3) The equation of this line may then be specified so that the position of other points in the graph (other environments) can be classified as falling above, on, or below the contour. Thus, the main contribution of the statistical manipulations was to provide a very enlightened guess as to how the line should be drawn. Much research effort was saved by selecting the right line with which to begin the critical part of the research.

could probably not endure the "intolerable" environments for more than a few minutes.

The criteria selected for this study indicate that the tolerance under consideration is an upper physiological limit. No work load is imposed; no task is set; no unusual clothing is worn; and establishment of thermal equilibrium is not required. The physiological limit has been surpassed when drastic subjective or objective symptoms occur. The tolerance level here defined falls just short of conditions which may be expected to cause complete failure due to heat exhaustion.

The contours are presented as a first approximation of this physiological limit and supporting data indicate that the three tolerance lines presented in Figure 17, along with contours from other studies, are essentially correct as to form, slope, and position. Further refinements of method and a larger body of data might suggest some curvature in the lines or slight modifications of the slope or position of the contours, but major alterations appear to be unlikely.

2. In a later study, Taylor and Marbarger (88) repeated some of these experiments on five nude subjects tested in ten environments with temperatures ranging from 100°F. to 154°F. and vapor pressure from 10 to 46 mm Hg. The same four physiological measures were evaluated, and it was shown that sweat loss could not be included in the index because it varied with certain environments independently of the degree of hyperthermia shown with some consistency by the other three measures. The evidence suggests that somewhat different physiological effects result from exposure to hot-dry as compared with hot-humid environments.

3. The AAF (33) describes another set of tolerable heat values which are more conservative but otherwise similar to those given by Taylor. These

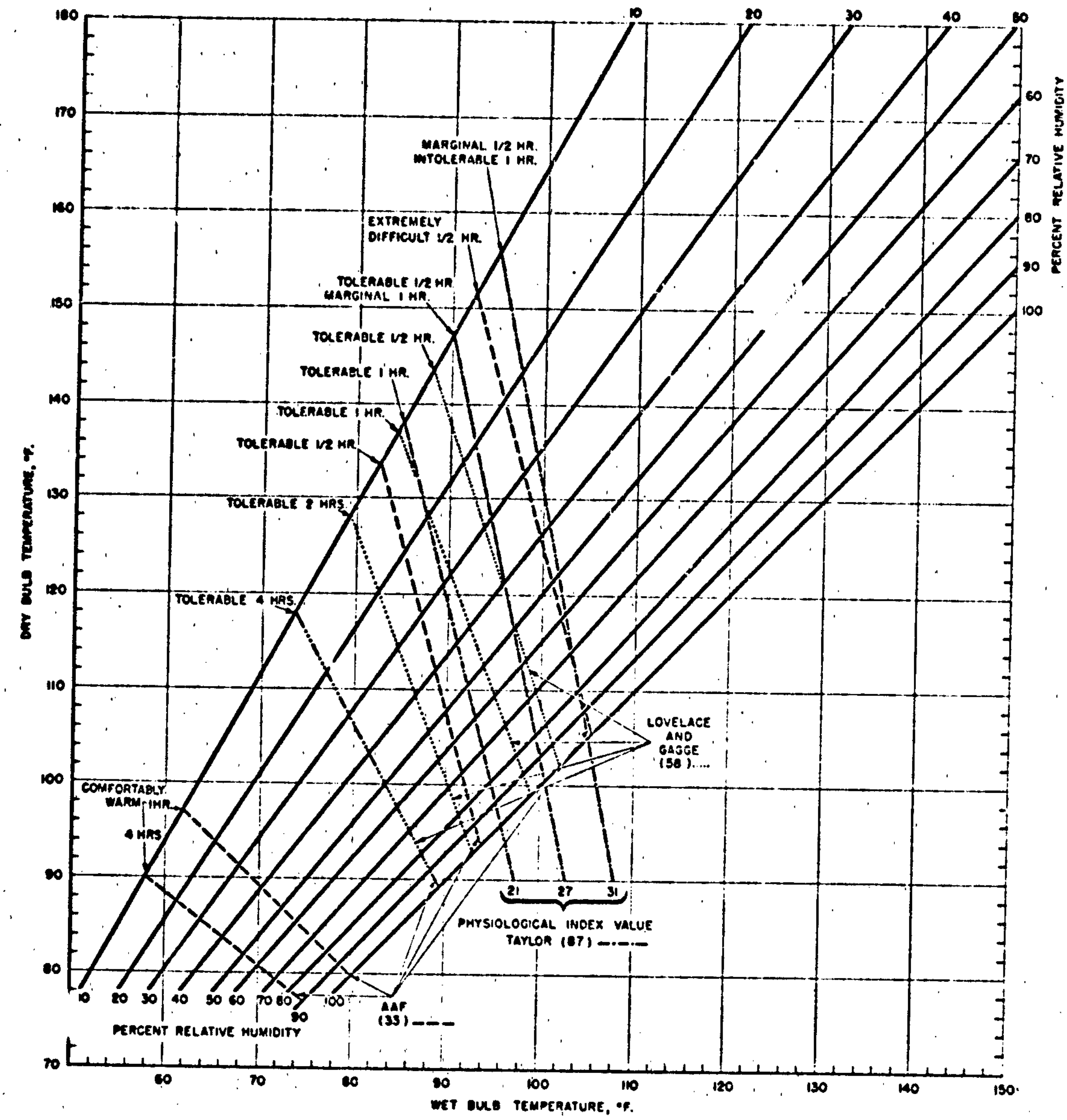

FIGURE 17 MAXIMUM TOLERABLE ENVIRONMENTS ACCORDING TO DURATION OF EXPOSURE, FOR SITTING, CLOTHED SUBJECTS. DATA FROM SEVERAL SOURCES.

are indicated separately in Figure 17, but they are actually based on the data reported by Taylor (86, 87) above.

4. Still another set of "maximum temperatures" are given by Gagge (33) in the following terms:

"For the warmer temperatures, the effect of humidity on comfort is great. For practical design purposes the maximum probable absolute humidity (30 mm of Hg vapor pressure) on the earth's surface should only be considered. For this absolute level of humidity, the upper comfort limit is 80°F.; 95°F. is tolerable for four hours; 107°F. for two hours; and 120°F. for one hour. These values, therefore, can well be used as a design requirement for aircraft without reference to its geographical use". The same standard has been more completely specified in a recent statement by Lovelace and Gagge (58). The experimental data upon which these contours are based are again those of Taylor (86, 87).

The maximum temperature which can be tolerated is not an absolute value but depends upon the work effort and duration of exposure. If this is kept in mind, it will be noted that there is general agreement as to where some particular tolerance contour should be drawn. Only one inconsistency is apparent in Figure 17. The AAF report gives as "tolerable for one-half hour" a set of conditions milder than those described as "tolerable for one hour" by both Taylor and Gagge and Lovelace. This apparent inconsistency, as well as the failure of some of the other tolerance lines to agree precisely, is due to the different assumptions employed in drawing the tolerance lines. Taylor's data, for example, represent maximum values for laboratory subjects under certain specified conditions. A military recommendation based upon such data might well be expressed conservatively in order to provide a safety factor and also to protect individuals slightly less tolerant than those on whom the tests were performed.

For purposes of reference, it is well to remember how these values compare with the reports previously noted in this paper. Robinson's experiment provides a tolerance contour applicable for men sitting at rest, where the criterion is maintenance of physiological equilibrium for six hours. That "maximum" (see the "E" line on Figure 13) would fall between the "tolerable for two hours" and "tolerable for one-half hour" lines on Figure 17, i. e., designated arbitrarily as originating at the juncture of approximately 130°F., dry bulb and 10 percent relative humidity. Obviously, the "inconsistency" between the two-hour level indicated in Figure 17 and Robinson's six-hour tolerance occurs because Robinson was concerned with a milder physiological stress than that adopted by the authors of the other contours on this figure.

The criterion of tolerance determines where the "maximum tolerance line" may be drawn. In the absence of further data, perhaps it is well to accept temporarily the more conservative lines offered here for the various durations. In effect, this is to adopt the values in present use for military aircraft, as given by Lovelace and Gagge and shown in Figure 17.

Taylor has continued at the University of California the studies of heat tolerance originated at Wright Field, but a formal report on these experiments is not available at this time. However, an interim report* was made to the Committee on Aviation Medicine of the National Research Council, in Washington, D. C., on June 22, 1948, and the following remarks are based on that report. Men, clothed in long underwear, have survived 20-minute exposures to a dry bulb temperature of 250°F. So that there will be no ambiguity concerning the significance of this astounding fact, it may be noted that this temperature is higher than that of boiling water. Body skin temperatures of 107°F. and heart rates of 150 beats

*"Human tolerance for extreme heat", to be published in the minutes of that meeting. The formal report will be made to the Air Materiel Command, Air Force, Wright Field.

per minute were recorded. Naturally, it is impossible to achieve equilibrium at these extremes and, in each case, the experiment was terminated at the imminent collapse of the subject. A chart shown by Taylor to demonstrate the relation between temperature and duration of exposure is reproduced here as Figure 18. Later phases of these experiments, which are now in progress, will extend the values of Figure 18 for a larger sample of subjects than the two men tested so far. In addition, an attempt will be made to collect performance data.

The study makes abundantly clear that hot air may be tolerated for brief periods at temperatures higher than those which produce burns upon contact. Pieron (74) and Dallenbach (21) agree in designating 122°F. as the limiting temperature above which contact with metal will result in the sensation of burning heat. Roberts (77) reports that 15-second contact with 212°F. and 30- to 60-second contact with 160°F. to 180°F. result in second degree burns. One conclusion which follows from Taylor's work is that gloves and other protective devices must be worn to protect the pilot from contact burns in hot environments where he may otherwise stand a chance of survival.

In conclusion, it must be re-emphasized that the tolerances given in this section refer merely to survival and bare avoidance of collapse. Comparison of these values with the tolerances based upon performance shows that the latter have more conservative values. Performance deteriorations have been reported at values below the most conservative tolerance contour of Figure 17("tolerable for four hours") This implies that there are some environments in which a man may continue without collapse for periods up to four hours and yet his performance on a psychomotor task would show deterioration before the end of the second hour, even though the task is so light that almost no work load is imposed. Tolerances defined in terms of physiological limits must not be applied to aircraft pilots on the assumption that the pilot's work-load is too small to alter such tolerance seriously. To do so

[redacted]

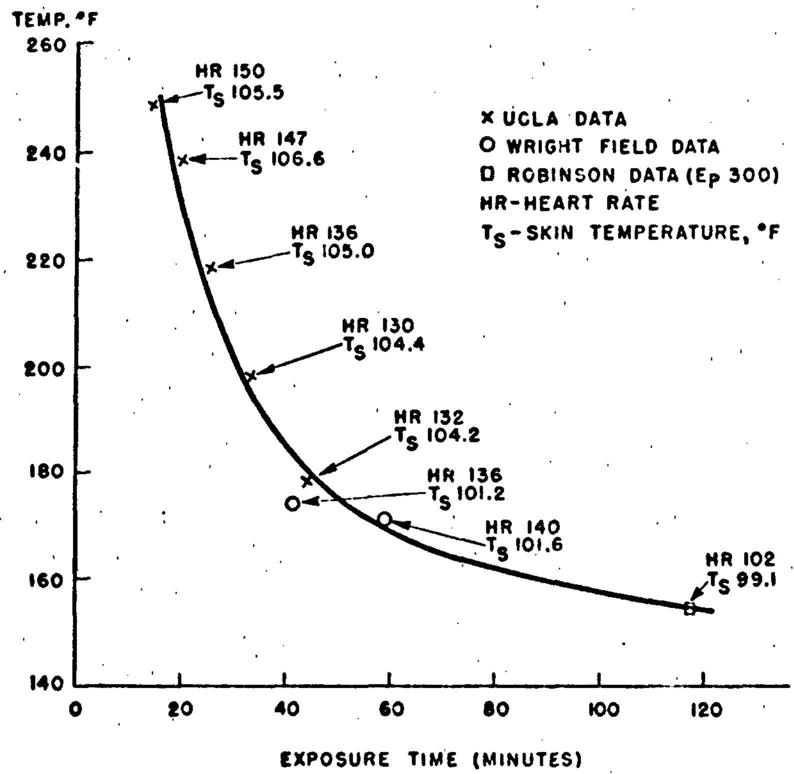

FIGURE 18 MAXIMUM TOLERABLE EXPOSURE TIMES FOR VARIOUS TEMPERATURES AT 12MM. HG. VAPOR PRESSURE, ACCORDING TO TAYLOR.

[redacted]

would carry the pilot beyond his ability to perform normally and place him in temperatures which would lead to significant impairment of his performance. Furthermore, modern aircraft are complex enough both in instrumentation and controls to tax the performance capacity of the pilot even in optimal temperatures. The performance studies to date are analytic in design: a single, relatively simple task is studied under varying thermal conditions. Whether the addition and complication of tasks will result in even lower temperature tolerances is not known. A reasonable guess is that deterioration may occur at less and less extreme conditions as the task becomes more elaborate.

[redacted]

Comfort Zone

VIII. The Thermal Comfort Zone

The American Society of Heating and Ventilating Engineers (101) have developed the concept of a "comfort zone", which they employ in specifying heating and ventilating standards. The significance of this concept in the present discussion is that it represents a range of thermal conditions which have been reported to be comfortable. While group opinion does not prove that thermal conditions are ideal either for organic adjustment or performance, it may be presumed, in the light of the studies which have already been reviewed, that no appreciable thermal stress is exerted so long as individuals feel comfortable. A person placed in environments defined by the "comfort zone" will be free from distraction or annoyance associated with a thermally uncomfortable surround.

The experimental procedure underlying the concept required that subjects rate their own sensation as cold, comfortably cool, very comfortable, comfortably warm, or too warm while in a room in which the temperature was progressively increasing or decreasing (97). The results are more applicable to exposures of limited than of prolonged duration. However, there can be little doubt that there is a central temperature band that will be reported as comfortable by most subjects. The limits of this band are not precise, and the band shifts upward during the summer (98). According to the ASHVE chart, the comfort zone is within the limits set by 72° to 85°F. on the 30 percent relative humidity line and 68° to 78°F. on the 70 percent relative humidity line. This area is demarcated in Figure 19, which also includes other specifications for the comfort zone. The area, as drawn, may be misleading unless it is realized that this study was limited to a humidity range of 30 to 70 percent and to rooms heated by ordinary methods. Thus, Mills (69) has shown that individuals could remain comfortable in a room at 93°F. and 70 percent relative humidity provided heat could be lost by radiation to cold plates on the walls of the room. In other experiments,

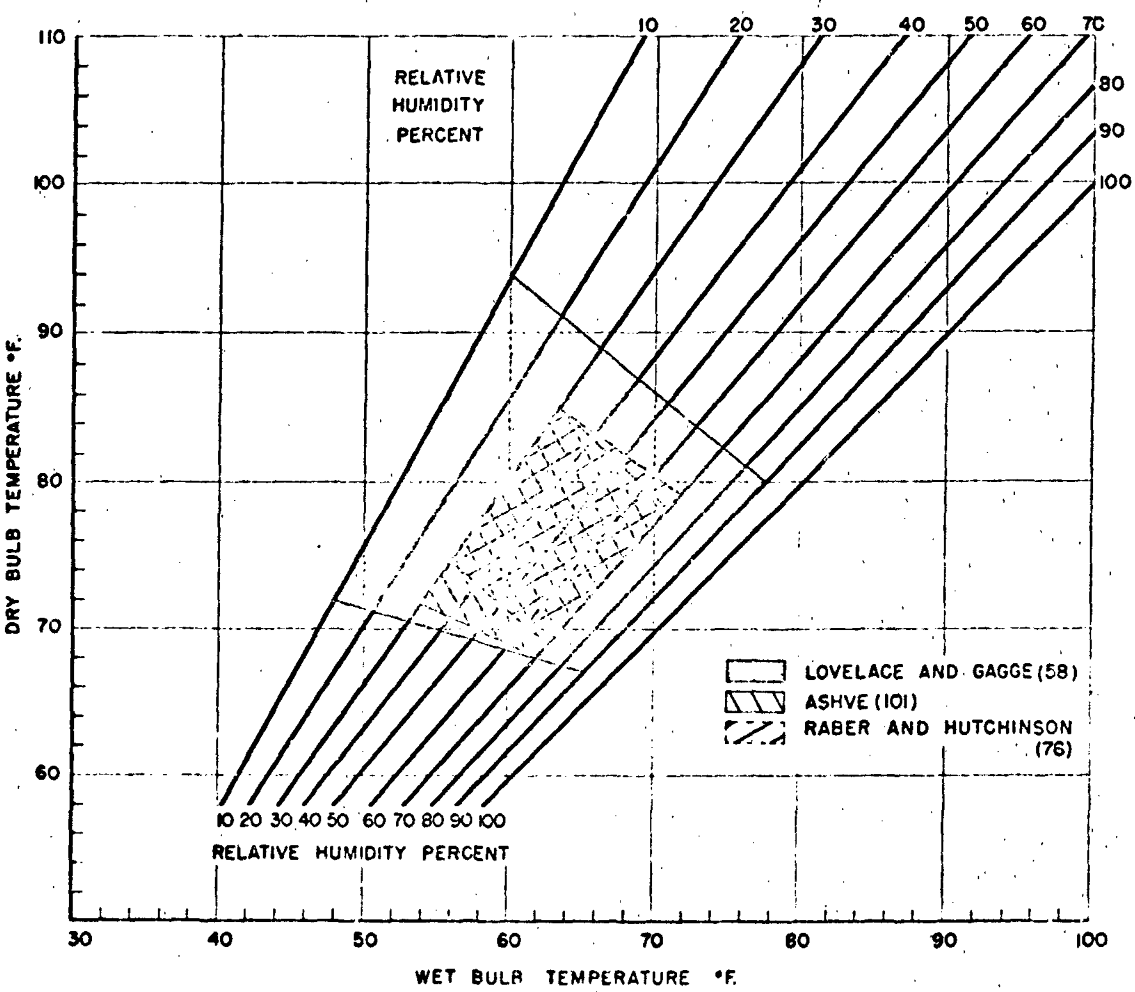

FIGURE 19 THE COMFORT ZONE AS DESCRIBED BY SEVERAL SOURCES.

low air temperatures (40°F.) were found to be comfortable, provided radiant heat was furnished from the wall plates.

An extension of the ASHVE comfort zone to include conditions which would be comfortable for small additional fractions of the population would enlarge the zone from 69°F. to 91°F. and from 66°F. to 83°F. on the 30 and 70 percent relative humidity lines, respectively. This extension, which is not shown in Figure 19, would involve within the given humidity range an area slightly greater than the area prescribed by Lovelace and Gagge.

Raber and Hutchinson (76), who base their comfort zone on the same experimental work, prefer a summer comfort zone bounded by 74°F. to 85°F. on the 30 percent relative humidity line and 69°F. to 79°F. on the 70 percent relative humidity line. These recommendations are also indicated in Figure 19. These authors indicate, moreover, that there is no evident health hazard in the extension of this band to 95°F. on the 30 percent relative humidity line and 90°F. on the 70 percent relative humidity line. The study points out health hazards are either known to exist or may be suspected at higher temperatures than those in the enlarged comfort zone. The area which is said to be free from health hazards has not been indicated in Figure 19.

The third area indicated in the figure is taken from Lovelace and Gagge (58). They define it as bounded by 72°F. to 94°F. on the 10 percent relative humidity line and 66°F. to 80°F. on the 90 percent relative humidity line.

Other authors have also attempted to specify a comfort zone, but their findings are considered separately because they appear to be less complete than those offered above. As an example, Brunt (16) considers the optimum zone to be 66°F. to 68°F., with relative humidity at 60 percent. The criterion was that, under these conditions, lightly clothed men could walk four mph in the sun

without sweating. Bedford (7) set the optimum range at 60°F. to 68°F. (with globe thermometer radiation readings of 62°F. to 68°F.). His specification rests upon the stated preference of 86 percent of 2600 factory employees. Boetjer (14) states that 68°F. to 73°F. is comfortable for light sedentary work if the relative humidity does not exceed 65 to 75 percent. Yagloglou (96) found an optimum at 64.5°F., at 100 percent relative humidity, which increased to 72°F. as relative humidity declined to 10 percent, for resting, normally clothed subjects. Armstrong (3) considers the optimum to be 50°F. to 85°F., with relative humidity 25 to 75 percent, for properly clothed pilots of aircraft. There are several other descriptions of the comfort zone in the literature, but they appear to be based on the work already reported or to reflect some special sort of working conditions.

Thus, there appears to be general agreement on the central core of the comfort zone as shown in Figure 19. The variations of opinion concerning the fringes of this zone are due (1) to differences in the range of humidities examined, (2) to the differences in application intended by their several authors, and (3) to the percentage of observers who must report discomfort before a particular temperature condition is declared to be uncomfortable.

In retrospect, this paper has described present available information concerning five broad zones of temperature. Progressing from mild to extreme, these regions are:

1. A comfort zone, wherein thermal equilibrium is maintained, performances are near optimum, and there is no reported distraction or discomfort due to thermal conditions. The ASHVE studies, reported by Yaglou (97, 98) and Houghten (49), serve to define the limits for this zone.

2. A marginal zone, standing immediately above the comfort zone, in which thermal equilibrium is maintained but where there may be reports of discomfort. Significant performance deterioration probably does not occur in

[redacted]

this zone, though the use of more sensitive tests than those which have been employed may lower the upper temperature limits of this zone. The studies of Mackworth (60, 65) and Viteles (91) define the upper boundary.

3. A performance deterioration zone is marked on the lower side by demonstrable impairment of performance and on the upper side by inability to maintain physiological equilibrium. Present evidence seems to indicate that performance may be impaired under conditions not extreme enough to occasion a loss of thermal equilibrium. This is the zone within which determination must be made of the amount of impairment which occurs on various tasks in the presence of uncomfortable, but still "tolerable" heat. The importance of this zone to the future aircraft pilot points to the need for further studies of performance under various combinations of thermal, as well as other, stress. See the studies of Robinson (80), Gagge (35, 95), and Taylor (87) for upper limits of this zone.

4. The survival zone includes a range of conditions too extreme for the establishment of thermal equilibrium yet not necessarily disruptive or lethal. The duration of exposure is very important among the conditions determining the upper limits of this region. By keeping the period of exposure short, very high temperatures can be survived and collapses avoided. This has been demonstrated by Taylor (87).

5. At still more extreme temperatures, collapse and/or death result.

None of the separating boundaries or tolerances has been defined with great precision. As the relevant studies are multiplied and refined, it will be even more apparent than now that the value for any particular temperature tolerance is not fixed but that it varies with a large number of accessory conditions. Presumably, when all external conditions are controlled, people will still be observed to vary in tolerance. In this case, a tolerance value must be used as a standard in a statistical sense: that certain events or symptoms occur with

known regularity at the given level of temperature. Thus, as Schickele's study shows, conditions can be found in which some rare individual will have a survival limit falling at a temperature and humidity scarcely above the comfort zone of others. One of the many interesting and unsolved theoretical problems is whether the several kinds of temperature tolerances tend to move upward and downward together as other conditions change or whether they are relatively independent of each other.

The general effect of high temperature upon performance may be stated, provisionally, in the following estimates based upon material reviewed in this paper:

1. "Normal" performances on moderately complex tasks which require little physical effort may be observed at <u>effective</u> temperatures up to 85°F.

2. Temperatures as high as 120°F. may be endured for about one hour, 107°F. for two hours, and 95°F. for four hours at the most severe humidities which occur under natural conditions. While it may be presumed that some deterioration in performance is demonstrable under these conditions, information is not yet available on the amount or quality of deterioration which appears on various tasks.

* * * * * *

As an addendum to the discussion of heat tolerances, brief mention will be made of the problem of raising tolerance and improving performance in hot environments. Research in this area has been directed primarily to three ways of increasing tolerance: through acclimatization, diet, and special clothing. Among these studies, not a few are essentially qualitative rather than quantitative experiments on performance. For example, in a study of acclimatization, Eichna (26) had men live continuously for four weeks in temperatures of 87°F. to 93°F., relative humidity, 80 to 96 percent. They walked 12.5 miles daily carrying 20 lb packs. At first they showed cardiovascular instability, rise of body temperature,

and apathy; and they worked slowly and painfully. About the eleventh day, however, the symptoms disappeared; and they worked almost as easily as in a cool environment. Evidently, as is generally agreed, performance improves as adjustment or acclimatization progresses. However, there is no quantitative statement of the improvement in terms of quantity or quality of performance or in terms of an increase in the severity of conditions which become tolerable subsequent to acclimatization. Using physiological criteria, Eichna also shows that acclimatization is attained rapidly by increasing daily the work load during continuous residence in a hot environment, whereas resting in the heat induces only slight acclimatization. Pace's study (73), which has been discussed above, is also relevant here. While his findings were not attended by a high degree of statistical significance, they suggest that there is less impairment of performance during an intermittent (sleeping in cool quarters at night) rather than a continuous prolonged exposure to heat.

Serious hindrances to acclimatization are inadequate water and salt intake and a previous lack of fitness. These findings are confirmed by Bock (13), who finds, in addition, that the nutritional requirements include the administration of water on an hourly basis, salt and sufficient food on a daily basis, and vitamins on a weekly basis. A high vitamin B supplement to the diet does not offer any advantage over a normal vitamin intake, as measured by the ability to do hard work in the heat (46). There have been conflicting reports upon the usefulness of adrenal cortical extract, which might have been expected to extend heat tolerance by its action in conserving salt. Some experimenters found it to have been helpful (20); and some have found it to be neither beneficial nor harmful (70). Adolph (100) stresses the importance of intermittent duty and rest and the avoidance of alcohol as ways to extend the tolerance. Under optimum conditions, an effective degree of acclimatization to heat develops within one

week; the Minnesota investigators (46) report that four to five days are required while the Harvard group (79) report that 80 percent of the acclimatization occurred in the first seven days of exposure. The latter group also indicate that 23 days were required for their subjects to reach maximum acclimatization.

The effect of clothing upon heat tolerance has been investigated primarily from the point of view of infantrymen rather than of pilots. The essential infantry requirement, which is not necessarily applicable to flight personnel, is that the clothing should be worn loosely to permit the dissipation of body heat while affording protection from solar heat (6). The use of infra-red barriers in clothing (lacquered metal strips) has been suggested by Burn (17) and Fourt (30) to reduce the heat load by reflecting heat radiated at the body. Houghten et al. (48) found that heavy work could be done at 110°F. (95°F. E.T.) by a man wearing a ventilated coverall suit when the air supply to the suit is cooled. Air ventilated clothing for pilots has been investigated by Marbarger (66) and for tank crews by a British group (38, 54, 104). Hutchinson (53) tested five anti-g suits during four hour exposures to tropical conditions (100°F., relative humidity 57 percent, and 90°F., relative humidity 71 percent). The men worked by stepping on a 12-inch high block 12 times per minute for two minutes every 15 minutes. All of the suits increased the rate of sweating and the accumulation of sweat in the clothing. A loose weave suit, worn without trousers, was most comfortable. According to Griffin (39), even an impervious suit over heavy clothing may be worn for four hours under jungle conditions (95°F., relative humidity 80 percent) before oral temperature reaches 101°F.

The problem of cooling the pilot of a plane becomes complicated when cabin pressurization does not provide sea level conditions. Heat exchange occurs by means of conduction, convection, and radiation, all of which, except for the last, are influenced by air pressure. As altitude increases, i. e., air pressure

[redacted]

decreases, the amount of heat exchanged by conduction and convection diminishes while the amount exchanged by radiation remains constant. In a relative sense, the <u>fraction</u> of heat exchanged by radiation increases with altitude while that of conduction and convection decreases with altitude. In effect, the more rarified air acts to insulate a body and to conserve its heat. These facts suggest that the possibility of cold "radiant" panels in the walls of the cockpit should be examined with a view to their usefulness as one means of cooling the pilot.

In accordance with available information, it may be concluded that the best performance under conditions of heat would be expected of acclimatized and rested individuals, provided with plenty of water and salt, and a normal amount of food. A recommendation on clothing would appear to be premature in view of the known complexity of flight clothing with respect to such factors as <u>g</u> protection, oxygen supply, communications, and safety gear (parachute, etc.). Consideration should be given to the possibility of incorporating a cool-air supply as one of the services offered by flight clothing.

[redacted]

APPENDIX

Effective Temperature:

Effective temperature is an empirically determined index of the degree of warmth perceived on exposure to different combinations of temperature, humidity, and air movement. It is based upon the judgements of trained subjects who rated their own relative warmth in rooms held at various combinations of temperature, humidity, and air movement. The index tends to emphasize the immediate impression created by exposure of limited duration to particular environmental conditions rather than the impression which remains after prolonged adaptation. The numerical value of the effective temperature index for any given condition is fixed by the temperature of saturated air which, at minimum air movement (15 to 25 feet per minute), induces a sensation of warmth like that of the given condition. The effective temperature chart which is shown in Figure 20 is applicable to inhabitants of the United States wearing light clothing, engaged in sedentary or light work, and in rooms heated by convection type systems. It would not apply to men in rooms heated by radiant methods. There is another chart applicable to subjects working while stripped to the waist (101). Effective temperature for any single value of ventilation may be superimposed upon the usual psychrometric diagram. This is shown in Figure 21 in order to demonstrate how the lines of effective temperature originate at the point of saturated air for each particular value of wet bulb temperature.

Reference: (101) p. 229; (97); (99).

Equivalent Warmth:

Equivalent warmth is a "provisional scale which takes into account all the warmth factors, viz., the temperature, humidity, and rate of movement of the air, and the radiation from the surroundings. The scale is referred to the standard

[redacted]

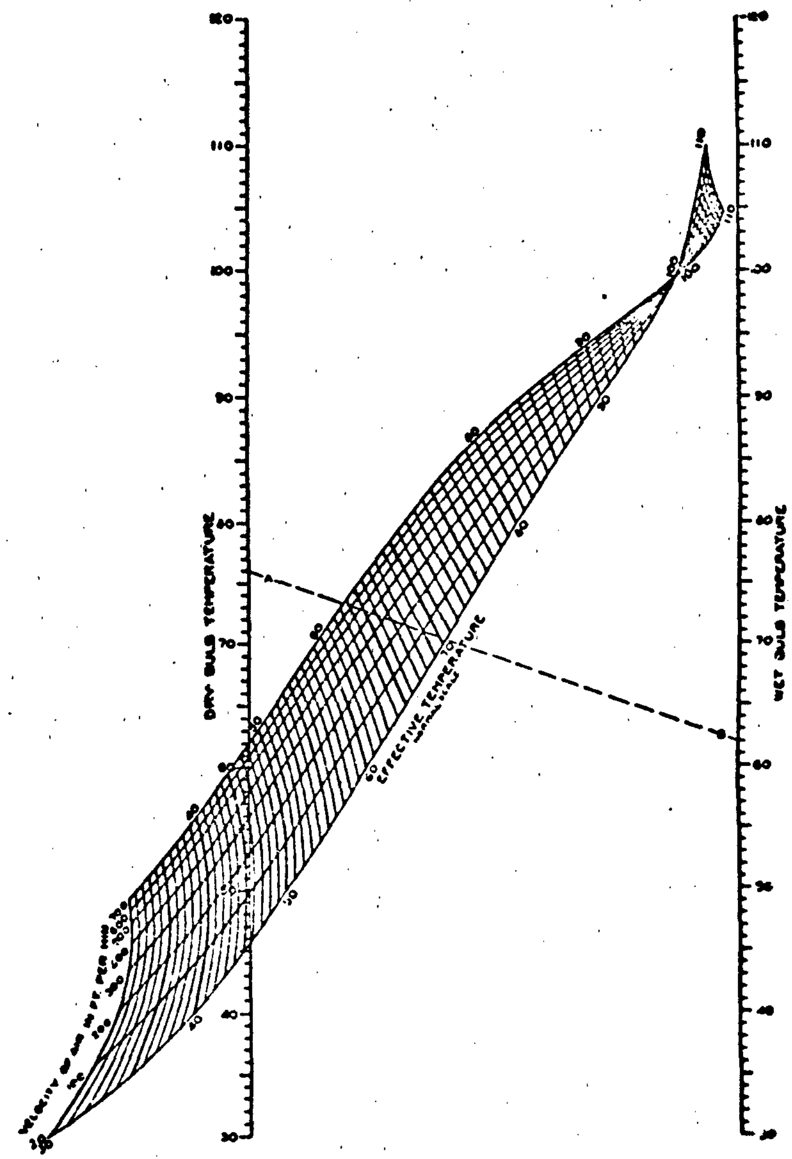

FIGURE 20 EFFECTIVE TEMPERATURE CHART DEVELOPED BY AMERICAN SOCIETY OF HEATING AND VENTILATING ENGINEERS. APPLICABLE TO NORMALLY CLOTHED PERSONS DOING LIGHT WORK INDOORS. (97)

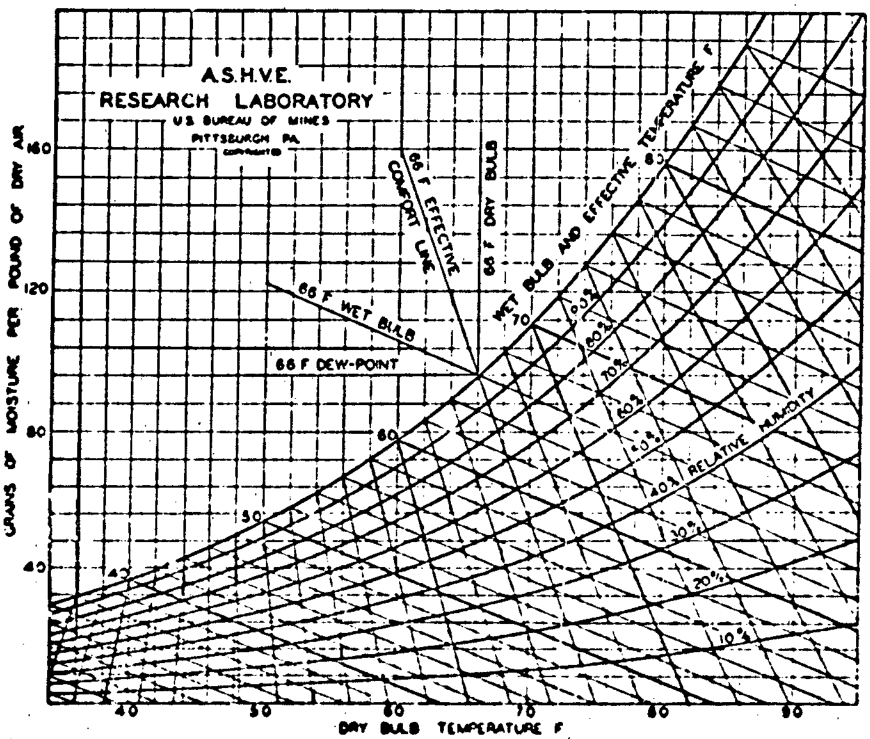

FIGURE 21 PSYCHROMETRIC CHART FOR PERSONS AT REST, NORMALLY CLOTHED, IN STILL AIR, SHOWING VALUES OF EFFECTIVE TEMPERATURE. (101)

[redacted]

conditions of a uniform enclosure with the air saturated and still". According to Bedford (8), the values of equivalent warmth are close to those of resultant temperature as arrived at with Missenard's resultant thermometer. A chart that may be used to calculate equivalent warmth is shown in Figure 22. The data which are required to use the chart are mean radiant temperature, vapor pressure, air velocity, and dry bulb temperature. If the vapor pressure is not known, wet bulb temperature (Scale E) and dry bulb temperature (Scale F) are connected by a straight line in order to read vapor pressure (Scale C). Then a line between radiant temperature (Scale A) and vapor pressure (Scale C) is used to read an arbitrary value at its intersection with Scale B. A line is then drawn between the value on Scale B and dry bulb temperature (Scale F). Equivalent warmth is read on Scale D, account being taken of the appropriate air velocity indicated on Scale D.

Reference (8) p. 35.

Standard Operative Temperature:

Standard operative temperature is a single value describing the net physical effect of the ambient air temperature and that of the surrounding walls, i.e., the combined influence of both radiation and convection. It includes values for ambient air temperature, mean radiant wall temperature, human body surface temperature, and air movement. Humidity is excluded since its only effect is on the efficiency of the evaporative regulatory process. The formula for calculating standard operative temperature is as follows:

$$SOT = \frac{K_R}{K_o}(T_W) + \frac{K_C}{K_o}\left[(\sqrt{V/V_o})T_A - (\sqrt{V/V_o} - 1)T_s\right]$$

where

K_R = radiation constant

K_o = cooling constant associated with operative temperature of the environment

[redacted]

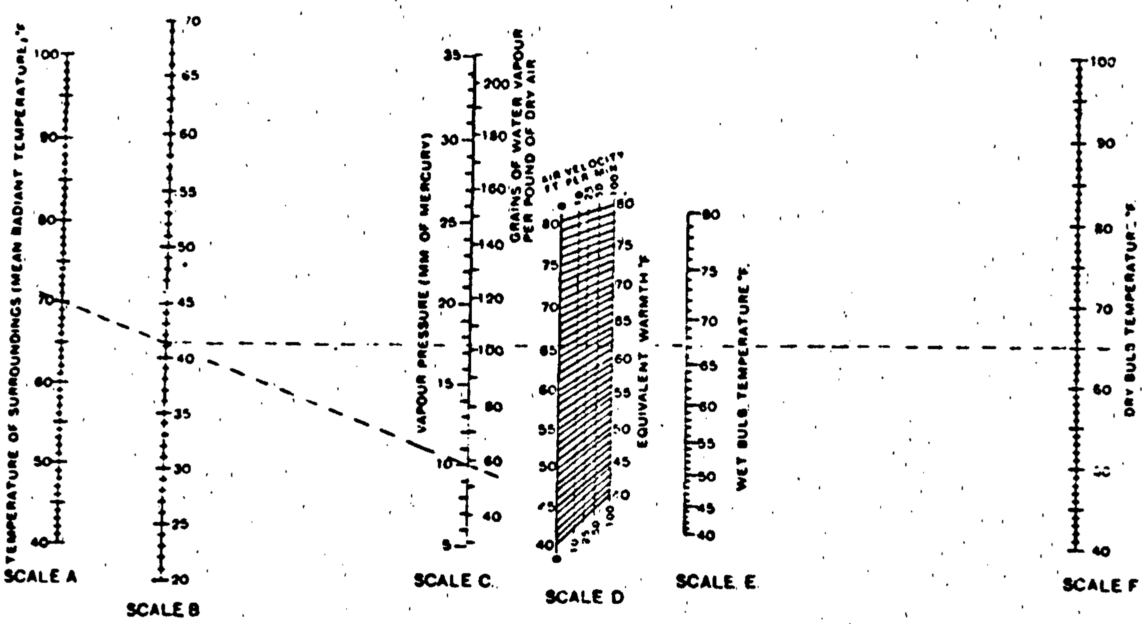

FIGURE 22 CHART FOR THE ESTIMATION OF EQUIVALENT WARMTH FOR NORMALLY CLAD PERSON DOING VERY LIGHT WORK. USE SCALE E AND F TO GET C; A AND C TO GET B; B AND F TO READ EQUIVALENT WARMTH ON D. TAKEN FROM BEDFORD (8).

T_W = mean radiant wall temperature

K_c = convection constant

V = air movement

V_o = standard air movement

T_A = ambient air temperature

T_s = surface temperature of body (human).

Reference: (32) p. 544-545; (35); (94); (95).

Psychrometric Chart:

A psychrometric chart is presented as Figure 23. There are separate, inter-related scales for dry bulb and wet bulb temperatures in degrees Fahrenheit, relative humidity in percent, vapor pressure in millibars and in millimeters of mercury, and grains of water vapor per pound of dry air.

[redacted]

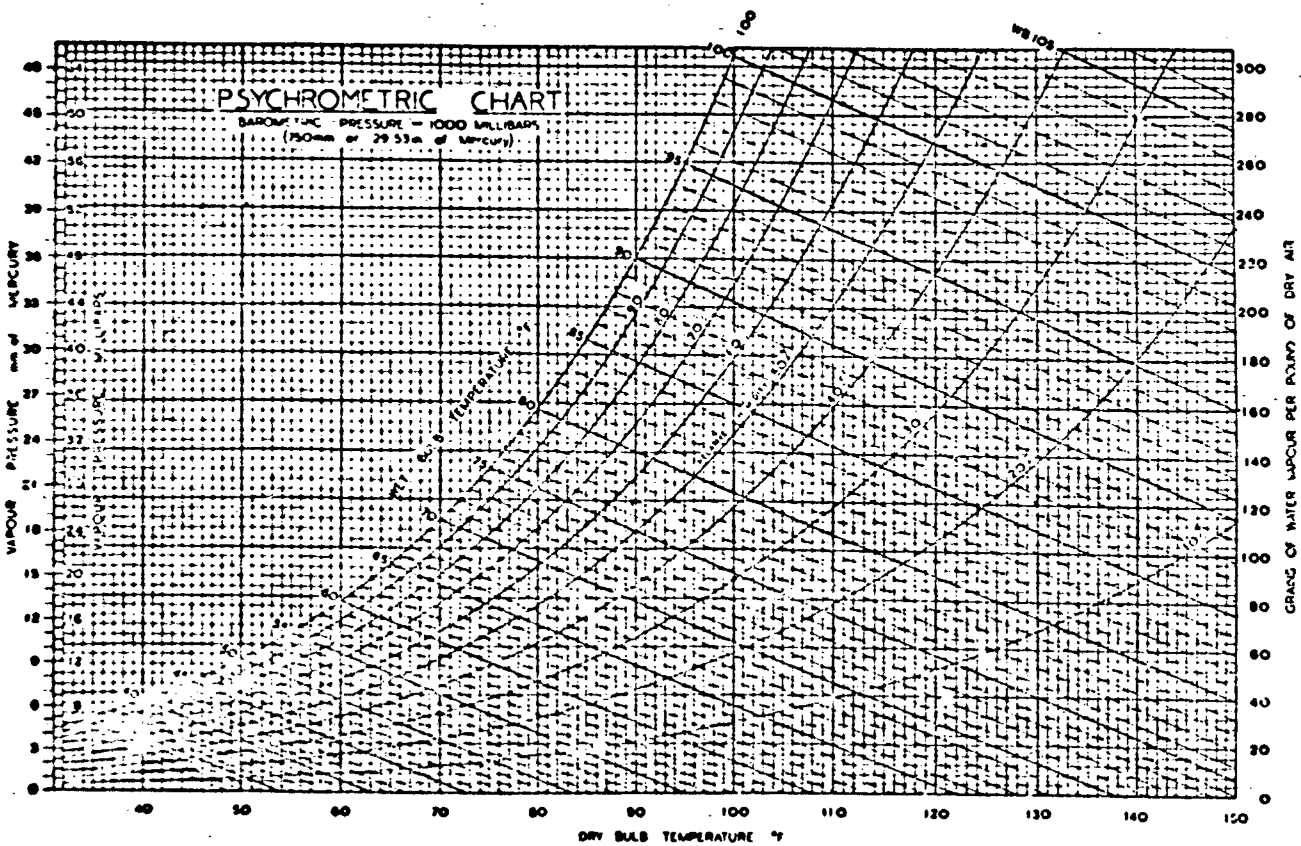

FIGURE 23 THE PSYCHROMETRIC CHART, SHOWING THE RELATIONSHIP BETWEEN DRY AND WET BULB TEMPERATURE AND HUMIDITY. TAKEN FROM BEDFORD (9).

BIBLIOGRAPHY

1. Adolph, E. F. Heat exchanges in man in the desert. Am. J. Physiol., 1938, 123, 486-499.

2. Anthony, R. A., Clarke, R. W., Liberman, A., Nims, L. F., Tepperman, J. & Welsey, S. M. Temperature and decompression sickness. NRC report No. 136, 26 May 1943.

3. Armstrong, H. G. The physiological requirements of sealed high altitude aircraft. War Dept., Air Corps, Tech. Report No. 4165, Dec. 19, 1935, Wright Field.

4. Armstrong, H. G. Principles and practice of aviation medicine. (2nd Ed.). Baltimore: Williams and Wilkins, 1943.

5. Bartley, S. H. & Chute, E. Fatigue and impairment in man. New York: McGraw Hill, 1947, Ch. VII, 99-134.

6. Bazett, H. C. (Chairman), Conference on working efficiency of high temperatures. 23 October 1945. Meeting of the Working Committee. Filed with: Reports, Comm. Clothing - undated (Rec'd NRC-CMR 15 January 1946).

7. Bedford, T. Requirements for satisfactory ventilation and heating. Human Factor, London, 1936, 10, 246-254.

8. Bedford, T. Modern principles of ventilation and heating. London: H. K. Lewis & Co., Ltd., 1937.

9. Bedford, T. Environmental warmth and its measurement. Royal Naval Personnel Research Committee of the Medical Research Council. 1946, War Memorandum No. 17, 3-40.

10. Best, C. H. & Taylor, N. B. The physiological basis of medical practice. (3rd Ed.). Baltimore: Williams and Wilkins, 1943.

11. Birren, J. E., Morales, M., White, W. A., & Iverson, H. R. Studies of the effect of air cooling on personnel aboard the U.S.S. Washington (BB56). Research Project X-205, Report No. 6, 12 April 1946, NMRI, Bethesda, Md.

12. Blum, H. F. The solar heat load: its relationship to total heat load and its relative importance in the design of clothing. NMRI, 23 May 1944.

13. Bock, A. V. Physiological adaptation of man to heat. Final report, OEM cmr-328, undated. On file NRC Library, Washington, D. C., received 19 November 1945.

14. Boetjer, A. M. Light, temperature, humidity effects in the working environment. Indust. Med., 1944, 13, 111-112.

15. Brobeck, J. R. Physiology of heat and cold. Ann. Rev. of Physiol., 1946, 8, 65-88.

16. Brunt, D. Climate and human comfort. Nature, 1945, 155, 559-564.

17. Burn, J. H. Notes on clothing for hot and cold climates. Report of the Comm. on Clothing, MPRC, 23 December 1942.

18. Clark, W. B., Johnson, M. L., & Dreher, R. E. Effect of excessive sunlight on the retinal sensitivity of an unprotected and completely protected eye in the same individual. Report No. 1 on Project X-567 (AV-295-p), 11 August 1945, NATC, Pensacola, Fla., Navy Department.

19. Code, C. F., Baldes, E. J., Wood, E. H & Lambert, E. H. The effect of environmental temperature upon man's *g* tolerance. Fed. Proc., 1946, 5 (1), 18.

20. Conn, J. W., & Johnstone, Margaret W. Improvement of ability of soldier to work in humid heat. OEMcmr-232 Monthly Progress Report No. 18, November 1945.

21. Dallenbach, K. M. & Lowenstein, E. The critical temperature for heat and burning heat. Amer. J. Psychol., 1930, 42, 423-429.

22. Darling, R. C., Johnson, R. E., Moreira, M. & Forbes, W. H. Suits, impermeable, protective. Harvard Fatigue Laboratory. Report #21, December 10, 1943.

23. Dill, D. B. Life, heat and altitude. Cambridge University Press, 1938, 94.

24. Dobriakova, O. A. The influence of taste, temperature and sound stimuli on the critical flicker frequency of monochromatic light. Probl. physiol. opt., Acad. Sci., USSR, 1944, 2, 81-84. (See Psychological Abstracts reference).

25. DuBois, E. F. The temperature of the human body in health and disease. In Temperature: its measurement and control in science and industry. (A symposium). New York: Reinhold, 1941, 24-40.

26. Eichna, L. W., Bean, W. B., Ashe, W. F. & Nelson, N. Performance in relation to environmental temperature: reactions of normal young men to hot, humid (simulated jungle) environment. Johns Hopkins Hosp. Bull., 1945, 76, 25-58.

27. Eichna, L. W., Ashe, W. F. & others. The upper limits of environmental heat and humidity tolerated by acclimatized men working in hot environments. J. Industr. Hygiene, 1945, 27, 59-84.

28. Fawcett, J. A. Desert flying conditions at Blythe, California. War Dept., Air Corps, Materiel Division, Exp-m-49-695-9, 30 July 1942.

29. Forlano, G., Barmack, J. E., & Coakley, J. D. The effect of temperature upon reaction time. U. S. Navy, ONR Memorandum No. 151-1-13, 15 March 1948. (Restricted).

30. Fourt, L. Infra-red reflecting fabrics as radiation barriers in clothing. CAM report No. 142, 20 September 1943.

[redacted]

31. François, M. Influence of internal temperature on our appreciation of time. C. R. soc. biol., 1928, 108, 201-203. (See Psychological Abstracts reference).

32. Gagge, A. P. Standard operative temperature, a single measure of the combined effect of radiant temperature, of ambient air temperature and of air movement on the human body. In Temperature: its measurement and control in science and industry. (A symposium). New York: Reinhold, 1941. 544-552.

33. Gagge, A. P. Human factors in aircraft design. U. S. AAF-ATSC. Engineering division. Aero Med. Lab. Memorandum report, TSEAL-3-695-53, 29 May 1945.

34. Gagge, A. P. & Herrington, L. P. Physiological effects of heat and cold. Ann. Rev. of Physiol., 1947, 9, 409-428.

35. Gagge, A. P., Herrington, L. P. & Winslow, C.-E. A. Thermal interchanges between the human body and its atmospheric environment. Am. J. Hygiene, 1937, 26, 84-103.

36. Garstens, M. A., Newell, H. E., Jr. & Siry, J. E. (Ed.). Upper atmosphere research report No. I, Navy Department, Office of Naval Research, Report R-2955, 1 October 1946.

37. Gemmill, C. L. Physiology in aviation. Springfield, Illinois: C. C. Thomas, 1943.

38. Gray, J. A. B. & McArdle, B. Physiological effects of ventilated suits in a Sherman tank in hot humid conditions. Report, Comm. Armoured Vehicles, MPRC, MRC-BPC, 44/384, October 1944.

39. Griffin, D. R. & Falk, G. E. Physiological tests of exposure suits. Harvard Fatigue Laboratory. Appendix 1. January 18, 1944.

40. Griffin, D. R., Robinson, S., Belding, H. S., Darling, R. C. & Turrell, E. The effect of cold and rate of ascent on aeroembolism. NRC Report No. 174, 22 June 1943.

41. Havens, R. J. & La Gow, N. E. Temperature measurements in the V-2. Upper atmosphere research report No. 1, Naval Research Lab., ONR, Navy Dept., Report R-2955, October 1946, 44-46.

42. Hecht, S., et al. Effect of sunlight on night vision. CAM report No. 420, 24 March 1945.

43. Heinemann, E. H. High speed aircraft developments. A paper presented before the American Society of Mechanical Engineers. National Aviation meeting, 1947.

44. Hemingway, A. Physiological effects of heat and cold. Ann. Rev. of Physiol., 1945, 7, 163-180.

45. Hemingway, A. Environmental temperature and swing sickness. J. Aviat. Med., 1946, 17, 86-88, 99.

46. Henschel, A., Taylor, L. H. Mickelsen, O. & Keys, A. Effect of high B vitamin intakes on ability of man to work in the heat. Report to NRC, Comm. Clin. Invest., 11 March 1943.

47. Hoagland, H. E. & Perkins, C. T. Some temperature characteristics in men. J. Gen. Physiol., 1935, 18, 399-408.

48. Houghten, F. C., Ferderber, M. B. & Gutberlet, C. Local cooling of workers in hot industry. ASHVE Journal Section, Heating, Piping and Air Conditioning, July 1941, 462-465.

49. Houghten, F. C. & Yaglogiou, C. P. Determination of the comfort zone. Tr. Am. Soc. Htg. and Ventil. Engrs., 1923, 29, 361.

50. Houston, C. S., Nuzie, S., Seitz, C. P. & Besson, G. E. Effect of temperature on anoxic failure in naval personnel in altitude chamber. Altitude Training Unit, U. S. Naval Air Station, Miami, Florida. Research Project X-396, Report No. 2, 8 August 1944.

51. Hulbert, E. O. The upper atmosphere of the earth. J. Opt. Soc. Amer., 1947, 37 (VI), 405-415.

52. Huston, W. B., Warfield, C. N. & Stowe, A. Z. Study of skin temperatures of conical bodies in supersonic flight. NACA Report No. L7J21. (Restricted).

53. Hutchinson, J. C. D. Physiological tests on flying clothing for use in the tropics. FPRC Report No. 624, May 1945.

54. Hutchinson, J. C. D. & McArdle, B. Physiological effects of wearing air-conditioned and other types of clothing in a tank in hot and humid conditions. Report, Comm. Armoured Vehicles, MPRC-BPC 43/189, March 9, 1943, and Addendum, December 4, 1943.

55. Johnson, C. L. Development of the Lockheed P-80A jet fighter airplane. J. Aeronaut. Sci., 14, December 1947.

56. Klein, W. H. Calculation of solar radiation intensity and the solar heat load on man at the earth's surface and aloft. War Dept. Memo., TSEAA 695-64, 20 February 1946, and Addendum No. 1, 17 June 1946.

57. Liberson, W. & Marques, P. Experiments on work at high temperatures in an artificial mine. Trav. Humain, 1934, 2 (1), 39-69. (See Psychological Abstracts reference).

58. Lovelace, W. R. II & Gagge, A. P. Aero medical aspects of cabin pressurization for military and commercial aircraft. J. Aeronaut. Sci., 1946, 13, 143-150.

59. Macpherson, R. K. & McGovern, P. B. The effect of tropical service upon the body weight of soldiers. 1-4, 3 tab., Secret Report Fatigue Lab. Nat. Health Med. Res. Council, Australia, 1945, No. 8. (Restricted).

60. Mackworth, N. H. Effects of heat and high humidity on pursuitmeter scores. Report, Subcomm. Habitability, RNPRC, MRC, RNP, 45/199, May 1945. (Restricted).

61. Mackworth, N. H. The effects of heat and high humidity on prolonged visual search as measured by the clock test. FPRC Report #586 (c), February 1946.

62. Mackworth, N. H. Effects of heat on wireless telegraphy operators hearing and recording Morse messages. Brit. J. Indust. Med., 1946, 3, 143-158.

63. Mackworth, N. H. High incentives vs. hot and humid atmospheres in a physical effort task. Brit. J. of Psychol., 1947, 38 (2), 90-102.

64. Mackworth, N. H. The breakdown of vigilance during prolonged visual search. The Quart. J. of Exp. Psychol., 1948, 1, 6-21.

65. Mackworth, N. H. Definition of the upper limit of environmental warmth by psychological tests of human performance. The Royal Society, Empire Scientific Conference Report, Vol.I, 1948, 423-441.

66. Marbarger, J. P. Air ventilated clothing. War Dept., Air Forces, TSEAL-695-2FF, 10 December 1945.

67. Martyn, D. F & Pulley, O.O. The temperature and constituents of the upper atmosphere. Proc. Roy. Soc. (London), April 1,1936, (A), 154 (882), 455-486.

68. McFarland, R. A. Human factors in air transport design. New York: McGraw-Hill, 1946, Ch. 4, 104-164.

69. Mills, C. A. Climate makes the man. New York: Harper & Brothers, 1942.

70. Moreira, M., Johnson, R. E., Forbes, A. P. & Consolazio, F. Adrenal cortex and work in the heat. OEMcmr-328. Report #127. Harvard Fatigue Lab. 6 October 1944.

71. Motley, H. L., Chinn, H. I. & Odell, F. A. Studies on bends. J. Aviat. Med., 1945, 16, 210-234.

72. Newell, H. E. Jr. & Siry, J. W. (Ed.). Upper atmosphere research report No. III, Navy Department, Naval Research Lab., NRL Report No. R-3120, April 1947.

73. Pace, N. Comparative study of the effect on men of continuous versus intermittent exposure to a tropical environment. Naval Med. Research Inst. Project #X-205 (2), 9 May 1945.

74. Pieron, H. On the inefficacy of thermal adaptation from the point of view of thresholds of burning. C. r. Soc. Biol., 1927, 97, 1930. (See Psychological Abstracts reference).

75. Pitts, G. C., Johnson, R. E. & Consolazio, F. C. Work in the heat as affected by intake of water, salt, and glucose. Harvard Fatigue Laboratory, Report #44 (OSRD Report #14). Also Am. J. Physiol., 1944, 142, 253-259.

76. Raber, B. F. & Hutchinson, F. W. Refrigeration and air conditioning engineering. New York: John Wiley & Sons, Inc., 1945, 291.

77. Roberts, L. B. & Mann, W. E. Methods of protection against flash burns. Armored Medical Research Lab., 13 November 1943.

78. Robinson, S. & Gerking, S. D. The effects of variation in environmental radiation upon the thermal exchange of working men. OEMcmr-351, Interim report #29, 30 November 1945.

79. Robinson, S. et al. Rapid acclimatization to work in hot climates. OEMcmr-54, Harvard Fatigue Lab., Report No. 17 (OSRD Report No. 2). 20 May 1942.

80. Robinson, S., Turrell, E. S. & Gerking, S. D. Effects of hot environments on men. Interim report #12, OEMcmr-351. Filed with: Reports, Comm. Clothing, 14 May 1944.

81. Root, C. J. & Stone, R. G. Deaths during the heat wave of July 1936 at Detroit. Bull. Amer. Meteorol. Soc., June-July, 1937, 232-236.

82. Sams, C. F. Medical problems of the Middle East. Annals of Int. Med., 1944, 21, 215-29.

83. Schickele, Elizabeth. Environment and fatal heat stroke: an analysis of 157 cases occurring in the Army in the U. S. during World War II. Mil. Surgeon, 1947, 100 (III), 235-56.

84. Smedal, H. A. & Brown, E. B. Incidence of bends at low temperature. U. S. Navy, BuMed. Letter, Aviation Supplement, Vol. 5, No. 11, p. 5.

85. Stalder, J. R. & Jukoff, D. Heat transfer to bodies travelling at high speed in the upper atmosphere. Reprint No. 128, Institute of the Aeronautical Sciences, New York, January 1948.

86. Taylor, C.L. Human tolerance for short exposures to heat. Army Air Forces, TSEAL-3-695-49A, 28 February 1945.

87. Taylor, C. L. Human tolerance for short exposures to heat and humidity. War Dept., Air Forces, TSEAA-695, 56D, 12 February 1946.

88. Taylor, C. L. & Marbarger, J. P. (by invitation). Some effects of extreme heat and humidity on man. Aero Medical Laby., Air Technical Service Command, Wright Field, Dayton, Ohio. Federation Proceedings, Vol. 5, No. 1, 1946, 104.

89. Vernon, H. M., Bedford, T. & Warner, C. G. The relation of atmospheric conditions to the working capacity and accident rate of miners. Ind. Fat. Res. Bd., Report #39, 1927, 34 pp.

90. Vernon, H. M., Bedford, T. & Warner, C. G. A study of absenteeism in a group of collieries. Industrial Fatigue Research Board, Report No. 51, 1928.

91. Viteles, M. S. & Smith, K. R. An experimental investigation of the effect of change in atmospheric conditions and noise upon performance. ASHVE Journal Section, Heating, Piping and Air Conditioning Guide, 1946.

92. Warfield, C. N. Tentative tables for the properties of the upper atmosphere. NACA Tech. Note, No. 1200, January 1947.

93. Weiner, J. S. & Hutchinson, J. C. D. Hot humid environment: its effect on the performance of a motor coordination test. Brit. J. Indus. Med., 1945, 2, 154-157.

94. Winslow, C. - E. A. Man's heat exchanges with his thermal environment. In Temperature: its measurement and control in science and industry. (A symposium). New York: Reinhold, 1941, 509-522.

95. Winslow, C. - E. A., Herrington, L. P. & Gagge, A. P. Physiological reactions of the human body to varying environmental temperatures. Am. J. Physiol., 1937, 120, 1-22.

96. Yagloglou, C. P. Modern ventilation principles and their application to sedentary and industrial life. J. of Personnel Research, 1925, 3, 375-396.

97. Yaglou, C. P., Carrier, W. H., Hill, E. V., Houghten, F. C. & Walker, J. H. How to use the effective temperature index and comfort charts. Heating, Piping and Air Conditioning, 1932, 433-437.

98. Yaglou, C. P. & Drinker, P. The summer comfort zone: climate and clothing. J. American Soc. of Heating & Ventilating Engineers, 1929, 35 (1), 1-15.

99. Yaglou, C. P. & Miller, W. E. Effective temperature with clothing. ASHVE Transactions, 1925, 31, 89.

100. Conference on Adverse Effects of Heat. Report #61. Reports Comm. Clin. Invest., 3 April 1945. (Restricted).

101. Heating ventilating air conditioning guide. New York: Am Soc. of Heat. and Ventil. Engr., 1944.

102. Statistics of Altitude Training Units. Aviation Medicine Division, Bureau of Medicine and Surgery. Navy Department, July 1944.

103. Temperature: its measurement and control in science and industry. (A symposium). New York: Reinhold, 1941.

104. Ventilated protective clothes for tanks crews. Report, Comm. on Clothing, MPRC-BPC, 42/84, July 11, 1942.

105. Ventilation: Report of the New York State Commission on Ventilation. New York: E. P. Dutton and Co., 1923.

END

DATE FILMED

9-19-67